DREDGED MATERIAL
RESEARCH PROGRAM

CONTRACT REPORT D-76-8

INVESTIGATION OF EFFLUENT FILTERING SYSTEMS FOR DREDGED MATERIAL CONTAINMENT FACILITIES

by

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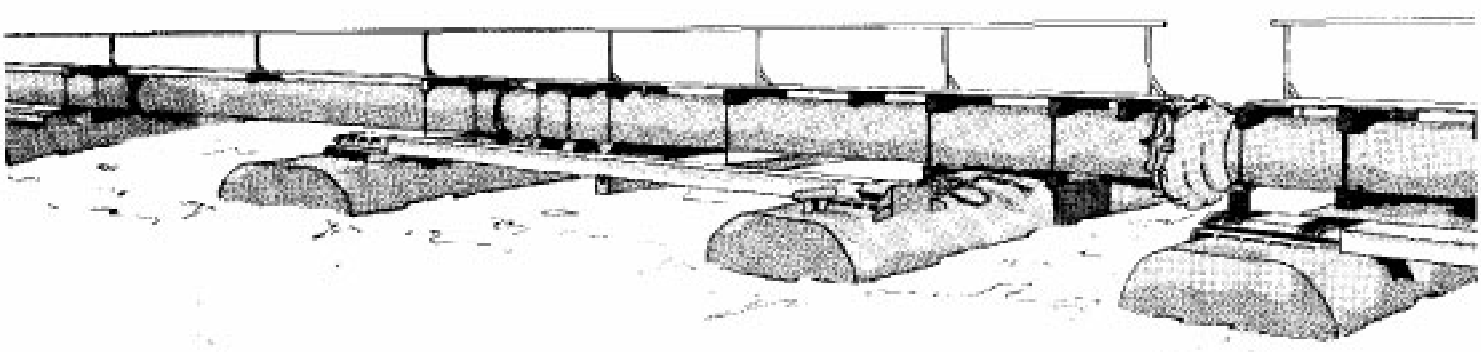

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This study was conducted to establish the functional capabilities and performance characteristics of effluent filtering systems and to provide guidance for the design of filtering systems to improve the quality of effluent from dredged material containment facilities. All available data were collected, pertinent literature was reviewed, and about 300 laboratory and field filtration tests were conducted. Conventional, technically feasible systems were identified, new concepts were developed (pervious dikes, sandfill weirs, (Continued)

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20. ABSTRACT (Continued)

forced-choice-triangle olfactometer. Although significant problems with malodors were not observed beyond the disposal area dikes during site visits, noteworthy odor episodes had occurred at some sites. An odor-abatement strategy is presented for handling the expected range of odor conditions at dredged material disposal sites. Its aim is to reduce to an acceptable level the perceived intensity of malodors in an affected community. The main steps in the strategy cover (1) selection of the disposal site, (2) site preparation, (3) odor characterization of sediments to be dredged, (4) malodor abatement during dredging and disposal operations, (5) malodor abatement after filling of the disposal site, and (6) the handling of malodor complaints.

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30 August 1976

SUBJECT: Transmittal of Contract Report D-76-8

TO: All Report Recipients

1. The contract report transmitted herewith represents the results of one research effort (work unit) initiated as part of Task 2C (Containment Area Operations) of the Corps of Engineers' Dredged Material Research Program (DMRP). Task 2C is included as part of the Disposal Operations Project of the DMRP, which, among other considerations, includes research into various ways of improving the efficiency and acceptability of facilities for confining dredged material on land.

2. Confining dredged material on land is a relatively recent disposal alternative to which practically no specific design or construction improvement investigations, much less applied research, have been addressed. There has been a dramatic increase in the last several years in the amount of land disposal necessitated by confining dredged material classified as polluted. Confining the material on land does not eliminate all problems associated with the spread or reintroduction of contaminants into the environment since the effluent or runoff from the areas must be considered. Since there is a wide variation in the effectiveness of disposal sites in removing suspended particulates and often associated contaminants, attention is being directed toward developing alternative methodologies for improving the quality of the effluent.

3. One method considered by the DMRP for improving disposal area effluent is the removal of suspended solids through filtration. The investigation, reported herein, was accomplished by the Department of Civil Engineering at Northwestern University. Its specific objective was to develop guidelines for the design of effluent filtering systems.

4. All available data were collected and pertinent literature on filtration processes was reviewed. In addition, about 300 laboratory and field filtration tests were conducted. Conventional, technically feasible systems were identified; new concepts were developed (pervious dikes, sand fill weirs, and granular media cartridges); and a general methodology was formulated for the design of containment facilities as solid/liquid separation systems.

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5. This study is considered to be an important step in developing a sound engineering approach to the design of effluent filtering systems. Design procedures are presented in this report along with example problems. All of the procedures and concepts appear technically sound and feasible, but little or no field performance data are available at this time. Implementation of these concepts is encouraged so that performance data can be obtained to establish the design validity under actual operating conditions. In addition, as results from field applications become available, the feasible systems can be refined to meet actual operating needs.

John L. Cannon
JOHN L. CANNON
Colonel, Corps of Engineers
Commander and Director

EXECUTIVE SUMMARY

Environmental concerns and/or economic considerations have resulted in a trend towards the disposal of dredged material in diked containment areas. In some cases, waterborne suspended solids and the associated contaminants may render the effluents from these disposal areas unacceptable for discharge to the open waters, and it may be necessary to employ some kind of treatment system. The work reported herein is directed toward evaluating a myriad of filter devices, systems, and concepts and developing a methodology by which appropriate effluent filtering systems for dredged material confinement facilities can be selected and designed. In a broader context this problem consists of identifying, evaluating, selecting, and integrating processes for dewatering dredged material slurries and/or clarifying disposal area supernatants.

The results of an extensive experimental investigation, including both laboratory and field filtration tests on granular media, were used to develop new concepts for the design of nonmechanized filter systems to clarify disposal area supernatants. These systems, which consist of pervious dikes, sandfill weirs with or without backwash, and granular media cartridges, have a relatively wide range of application with respect to the concentration of suspended solids in their influents. Pervious dikes, which may be used for influents with concentrations of suspended solids up to 0.5 g/ℓ, constitute a low maintenance filter that is characterized by very large filter depths and intended for a long effective lifetime. Sandfill weirs without backwash require maintenance to replace clogged filter media at periods significantly shorter than pervious dike lifetimes; although the type of influent to be treated with this system is similar to that for pervious dikes, its mode of operation is much more flexible. For cases where the influents are expected to have suspended solids concentrations up to 1 or 2 g/ℓ, the sandfill weir offers an attractive alternative. Granular media cartridges can be used with waters having loads of suspended solids up to 10 g/ℓ; however, maintenance requirements are expected to be excessive at loads higher than a few grams per liter.

Removal efficiency and expected lifetime are two important characteristics of filter media to be used in any design. To assist in the design of granular media filter systems, nomographs were developed to allow (a) the effective grain size or the depth of the filter medium and (b) the time before severe clogging occurs to be estimated from a knowledge of the required removal efficiency and the concentration of suspended solids in the influent. Gravity sedimentation of dredged material is a natural process that dramatically affects the quality of the effluents from disposal areas. Classical sedimentation basin theories were adapted and nomographs were prepared to estimate the amount and gradation of suspended solids in the effluents of a disposal area (or the influents to a filter system) when the geometry of the area, the flow rate, and the pertinent characteristics of the dredged material slurry are known.

Based on an extensive literature review, it was found technically feasible to use (a) vacuum filtration for dewatering dredged material slurries with 10 g/ℓ or more solids content, (b) a special microscreen device to clarify waters with up to 1 or 2 g/ℓ of suspended solids, (c) special designs of deep bed filters (such as moving bed, upflow, or pressure) to clarify waters with up to 1 g/ℓ suspended solids, and (d) conventional mechanized deep bed filters to treat waters with suspended solids concentrations up to several hundred milligrams per liter. Nonmechanized surface filtration systems using fibrous media were found to be generally unable to provide high removal efficiencies and sustain long runs. Electrofiltration appears uneconomical and it is not yet developed to the stage of field applications. Although the technical feasibility of using the foregoing variety of filter systems has been reasonably well documented, field evaluations are considered necessary and cost-effectiveness studies will further clarify the potentials of each system.

PREFACE

The work described in this report was performed under Contract DACW-39-74-C-0090 (neg) entitled "An Analysis of the Functional Capabilities and Performance of Pervious Dikes, Sandfill Weirs, and Related Effluent Filtering Systems," dated 29 March 1974, between the U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi, and Northwestern University, Evanston, Illinois.

For their help in the successful completion of this investigation, grateful acknowledgments are extended to:

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John T. Fornek, graduate student at Northwestern University, for conducting the laboratory tests on fibrous media, processing the associated data, and assisting in the interpretation and evaluation of the results.

Dominic M. Delle Grazie and Theophille Felton of Northwestern University for their assistance and advice in constructing the various pieces of equipment needed for this work.

This research was sponsored by the Dredged Material Research Program (DMRP) which is administered by the Environmental Effects Laboratory (EEL) of WES. The study was conducted under Task 2C, "Containment Area Operations," Mr. Newton C. Baker, Manager, as part of the Disposal Operations Project managed by Mr. Charles C. Calhoun, Jr. The contract

was managed by Messrs. Andrew J. Green and Raymond L. Montgomery under the general supervision of Dr. John Harrison, Chief, EEL. The contracting officer was COL George H. Hilt, CE, Director, WES. Technical Director was Mr. Frederick R. Brown.

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INVESTIGATION OF EFFLUENT FILTERING SYSTEMS FOR DREDGED MATERIAL CONTAINMENT FACILITIES

PART I: INTRODUCTION

1. With the rapid advance in urban growth and industrial development, as well as the extensive use of various chemicals for agricultural applications, the sediment dredged from deep water harbors and channels has become increasingly contaminated. Recent concerns for the environment, as well as economic considerations in some instances, have dictated that open-water disposal be abandoned in certain cases, and a trend has developed toward the disposal of dredged material in diked containment areas. Approximately 70,000,000 yd^3 (53,000,000 m^3) of material from maintenance dredging are currently handled in this manner (Boyd et al., 1972), and all evidence indicates that this volume will increase continuously during the ensuing years.

2. Among the many problems and controversies associated with such dredging and disposal operations is that of satisfying imposed water-quality standards for the disposal area effluents that are released back into the open water. Although these water-quality standards are highly variable at this point in time and dependent largely on the background and experience of local authorities, there is a definite trend toward the adoption of stricter criteria. As these standards become more stringent, additional burdens will be placed on effluent treatment systems to ensure compliance. Accordingly, the work reported herein was directed toward providing the background information and experience required to address this problem. Specifically, this research effort consisted of analyzing the functional capabilities and performance characteristics of pervious dikes, sandfill weirs, and other filtering systems for disposal area effluents; and its primary objective was to provide guidance for the design of filtering systems to improve the quality of effluents from dredged material containment areas by controlling the amounts of suspended solids.

3. Processes for removing finely divided suspended material from waters have been used for centuries. The ancient Egyptians purified water by passing it through sand beds, and the earth's mantle is known to provide excellent filtration capabilities. However, only recently has the science of filtration been put on a basis that is sufficiently rational to allow the quantitative modification of traditionally empirical designs. Nevertheless, the optimization of filtration techniques is still in the initial stages of development, and many aspects of the phenomenon have yet to be investigated before efficient filtering systems can be designed with little or no experimentation.

4. The need for this study arose in large part by the fact that the filtration of dredged material slurries, or literally fine-grained soil suspensions, has not been conducted under the wide range of conditions that may be encountered in various phases of a typical dredging and disposal operation. Most of the mechanistic investigations of filtration have been quite narrow in range and were performed on filter systems that are suitable only for the treatment of municipal or industrial waters and wastewaters, and specific data and design guidelines pertinent to the scope of this research were found quite lacking in the literature. To satisfy this need, an extensive experimental program was undertaken to evaluate quantitatively the characteristics and capabilities of different filter media under a wide variety of conditions. The levels of suspended solids, the flow rates, and the types and sizes of the filter media that were examined in this study probably constitute one of the most extensive experimental parameter studies on water filtration. In addition to the experimental investigation, an extensive literature review of solid-liquid separation technology was undertaken so that the conceptual development of systems for dewatering dredged material slurries and clarifying disposal area supernatants could be founded on a broad base of developments that have been advanced in the last decade.

5. A review of disposal area design and operation from the standpoint of effluent quality control, an overview of filtration techniques, a summary of dredged material characterization data that formed the

basis for the experimental part of this study, and a discussion of previous work on the filtration of clay suspensions are presented in Part II. Included in Part III are the rationale behind the experimental plan, descriptions of all tests that were conducted, the parameters that were varied, the equipment and techniques that were employed for each test, and the data collection procedures. The results of the laboratory and field tests, the observations that were made, and the conclusions regarding the characteristics and performance capabilities of the filter media investigated are given in Part IV, and this is followed by the presentation of design considerations, guidelines, and criteria for the optimum use of granular and fibrous filter media in dredged material confinement facilities.

6. An assessment of the characteristics, performance capabilities, and design concepts of pervious dikes, sandfill weirs with and without backwash, and granular media cartridges, is given in Part V. Based primarily on expected influent and desired effluent quality, the conditions conducive to the most effective operation of conventional and conceptually new filter systems are described in Part VI, and filter systems are proposed to handle the variable conditions associated with each of several different characteristic disposal operation scenarios. Finally, the work that has been accomplished is summarized and evaluated in Part VII, and suggestions are offered for further investigations.

7. Data on the chemical constituents and grain-size distributions of bottom sediments from a large number of locations around the United States are summarized in Appendix A. The development of a correlation between turbidity and mass concentration for the Grundite and kaolinite suspensions used in the experimental part of this study is presented and explained in Appendix B. In Appendix C, the results of a limited vacuum filtration laboratory test series are summarized. Classical solid-liquid separation technology for coagulation and flocculation, sedimentation, and filtration, as well as pertinent recent developments, are reviewed in Appendix D, and this review is followed by a dicussion of the compatibility, advantages, and disadvantages of mechanized and non-mechanized filter systems with respect to disposal area operations.

PART II: BACKGROUND

8. Diked areas for the confinement of dredged material have been in use for many years (Murphy and Zeigler, 1974). In recent years, however, the amount of dredged material being confined on land has continuously increased relative to the amount deposited in open water, and a variety of problems related to the confined disposal of dredged material have occurred. The quality of the effluents discharged from the containment area into the main body of water frequently poses a major problem. Among other factors, effluent quality is affected by the nature of the dredged material, the size of the disposal area, the operating conditions that prevail within the area, and the method of effluent discharge; and whether or not these effluents satisfy the imposed regulatory criteria is, to a large extent, dictated by the control that is exercised on the concentration of suspended solids in the effluents. Accordingly, the principal objectives of the research effort reported herein were (a) to establish the functional capabilities and performance characteristics of effluent filtering systems and (b) to provide guidance for the design of filtering systems to improve the quality of the effluent from confined disposal areas. The following information provides the background that was used to design the overall research program to meet these objectives; included are (a) a review of disposal area design and operation from the standpoint of effluent quality control, (b) an overview of filtration techniques, and (c) a summary of the characterization data that formed the basis for the experimental part of this study.

Disposal Area Effluent Control

9. Although land disposal of dredged material continues to increase in usage over open-water disposal, there is a general lack of complete records on diked disposal area operations (Murphy and Zeigler, 1974). There are two primary reasons for this situation: first, the dredging contractor is responsible in many cases for the construction,

operation, and maintenance of the containment facilities and specific details and procedures pertaining to each contract are generally not recorded; and second, little attention has been given to the disposal of dredged material. The efficiency of a dredged material containment facility is affected by the size of the area, the method of disposal, the kind and quality of dike and sluice facilities, and the operation of the site during disposal.

10. All confined dredged material disposal areas, with the exception of those where dewatering of the dredged slurry takes place by evaporation, are equipped with some kind of sluicing device. Sluices vary from a simple outfall pipe to large wood, steel, or reinforced concrete structures with one or more discharge pipes and weirs with adjustable crest elevations. These structures serve the dual function of allowing the water to drain rapidly from the disposal area and helping to control the effluent quality. However, despite the important role of effluent discharge systems, sluice design has not received appropriate attention; weir design and construction is not standardized; and little is known about the effect of weir characteristics on effluent quality (Murphy and Zeigler, 1974). In a limited number of disposal areas in the Great Lakes Region, the sluicing device has been replaced by a filter system. Two disposal areas in the Buffalo Harbor were designed with slag-filled dikes; two disposal areas in the Cleveland Harbor incorporated a pervious dike and a stone filter on the interior face; and a plastic filter cloth was tested in the Charleston District (Murphy and Ziegler, 1974). In addition, a vertical sand filter design is proposed for a new disposal area to be constructed in the Milwaukee Harbor (U.S. Army Corps of Engineers, Chicago District, 1972). However, information to date on the performance of such filtering systems is extremely limited.

11. Murphy and Ziegler (1974) reported that measurements for one of the Buffalo Harbor pilot sites indicated that there was no significant difference in the quality of the water inside the disposal area and that in the harbor immediately outside. Efforts in this present study were unable to determine even the existence of these performance

data. The results reported for one pilot site in the Cleveland Harbor (U.S. Army Corps of Engineers, Buffalo District, 1969) indicated that, for the conditions associated with the existing disposal operation, the pervious dike did not have a significant filtering effect, except to retain floating debris and oil. Satisfactory drainage of water was achieved at both sites, and no difficulty was apparently encountered from clogging of the pores in the pervious dikes or filter blankets; this observation may indicate that the dikes were too pervious. Tentative results from the Charleston District study (Murphy and Zeigler, 1974) suggest that filter cloths may be used to effectively retain solids.

Effluent quality standards

12. One of the important functions of a dredged material containment facility is to provide effluents that comply with existing and projected quality standards. Listed in Table 1 are several typical effluent quality standards as of 1973 (Murphy and Zeigler, 1974) and as of early 1975; this limited survey indicated that for the last few years (a) a single nationwide standard did not exist and (b) different parameters were used in different Districts to assess effluent quality. Some Districts were permitted to discharge large amounts of solids in the effluents of disposal areas (enough to increase suspended solids by 4 to 13 g/ℓ above ambient); others specified very low amounts of suspended solids (turbidity readings equal to those of the receiving water increased by 50 JTU or solids concentration equal to that of the receiving water increased by 50 percent); and still others had no set standards. The values listed in Table 1 suggest the tendency towards stricter effluent quality criteria over the past few years. Further analysis of these quality control criteria reveals that, for the usual operations where dredges pump slurries with between 10 and 20 percent solids by weight, (a) the ability to meet an 8 g/ℓ above-ambient effluent standard requires only about an 80 to 90 percent solids retention efficiency for the containment area, (b) for ambient waters with low levels of suspended solids, the ability to meet a 50 JTU above-ambient effluent standard requires a very high retention efficiency (perhaps more than 99 percent), (c) for a water sample with measurable turbidity, a very

Table 1

<u>Water Quality Standards for Disposal Area Effluents</u> +

District	1973	1975 Standards	Person Contacted	Date
Galveston	8 g/ℓ above ambient	8 g/ℓ above ambient	Mr. Keesecker	3/20
New Orleans	None set	1.5 x ambient concentration	Mr. Garret	3/20
Mobile	None set	50 JTU above ambient	Mr. Pruett	3/20
Jacksonville	50 JTU	50 JTU above ambient	Mr. Hamilton	3/20
Savannah	None set	--	Mr. Roberts	3/21
Charleston	None set	--	Mr. Kyzeo	3/21
Wilmington	50 JTU	50 JTU above ambient	Mr. Frazelle	3/21
Norfolk	13 g/ℓ above ambient	13 g/ℓ above ambient	Mr. Thilpott	3/20
Philadelphia	8 g/ℓ above ambient	8 g/ℓ above ambient* 4 g/ℓ above ambient**	Mr. Kreh	3/21
New York	8 g/ℓ above ambient	1.5 x ambient concentration	Mr. Boutin	3/21
Buffalo	50 ppm settleable solids	None set	Mr. Carpenter	3/25
Detroit	8 g/ℓ above ambient	No standards	Ms. McLean	3/20
Chicago	None set	None set	Mr. Parez	7/16
Sacramento	8 g/ℓ above ambient	6 g/ℓ above ambient	Mr. Bitow	3/21
Portland	5 JTU	1.5 x ambient concentration	Mr. Haigh	3/20
Seattle	5-10 JTU	5 JTU (state requirement) 5 g/ℓ above ambient (Corps criterion)	Mr. Juhnke	3/21
Los Angeles	--	None set	Mr. Ackerman	3/20
San Francisco	--	None set	Mr. Stratton	3/20

*Small size areas   **Large size areas

+Standards were State imposed or voluntarily imposed by the District in cases where no State standards existed small amount of suspended solids (not more than 0.1 g/ℓ can easily increase the turbidity by 50 JTU, and (d) the 50 percent above-ambient concentration is a very ambiguous standard that can lead to requirements of very low or excessively high retention efficiency for a given containment area.

13. New interim guidelines were recently imposed (EPA, 1975) to govern the discharge of dredged or fill material into navigable waters. These new guidelines require a case-by-case evaluation of discharges from confined disposal areas to ascertain that "appropriate and legally applicable" water quality standards are satisfied at the boundaries of an appropriately defined mixing zone. An interagency manual prepared by the U.S. Army Corps of Engineers and the Environmental Protection Agency will define tests, procedures, calculations, etc. necessary to evaluate such discharges, but this document is not yet available. As water quality improves to achieve the full objectives of the new guidelines, it is anticipated that discharge limitations will become more stringent, but exactly how regulations concerning suspended solids in these discharges will be affected is unknown at this time.

Identification of effluent control problem

14. With an adequate understanding of the existing effluent quality standards and the variability in the size of disposal areas, the problem of controlling suspended solids in disposal area effluents can be identified as follows:

- a. Districts that can provide large disposal areas and must comply with lenient effluent quality standards should have no need to incorporate any filter control systems in the design of their containment facilities; adequately long detention periods and proper crest elevations of the overflow weirs can satisfactorily control effluent quality.
- b. Operations where strict effluent quality standards must be satisfied will probably require the use of control units, such as filtering systems composed of granular media, fibrous media, or combinations of both; the concentration of suspended solids in the influent to such systems will determine the type of system, including operation, control, maintenance, energy requirements, and costs.

c. Future operations may involve the use of small disposal areas as transfer or process stations, as opposed to permanent containment areas for dredged material. Filtering systems for such areas may constitute an important component of the facility, and the systems must satisfy the twofold function of producing an effluent of acceptable quality while rapidly dewatering the dredged material so that it can be handled by bulk solids handling equipment. Vacuum filters or centrifugation equipment appear to be appropriate, although costly, alternatives for this purpose.

Overview of Filtration Technology

15. There is an abundance of literature on the filtration of suspensions and slurries containing inorganics (clays, metal oxides, and hydroxides) and organics in fuel and mineral processing, as well as in water and wastewater treatment. The most pertinent studies within the scope of this research are those dealing specifically with clay-water separation by porous solid contact. Much of the available information is found in the literature on sanitary, chemical, and mineral engineering and clay colloid chemistry. Sanitary engineers have provided insight into the design of deep bed filters for clarification, while mineral processing and chemical engineers have directed efforts to advance the theory and practice of filtering concentrated suspensions to recover the solids. Although not of direct concern in this work, engineers have sought the assistance of clay colloid chemists to develop improved separation or solids recovery techniques by manipulating chemical factors in the process stream. Recent attention has been given to the rather difficult problem of selecting the appropriate separation technique for a given application (Tiller, 1972; Fitch, 1974; Emmett and Silverblatt, 1974; and Tiller, 1974). Convenient flow charts to guide the design of bench tests for selecting the right equipment and pretreatment (Tiller, 1974) or tables to classify filter types based on suspension type and filtration characteristics (Alt, 1975) are available.

16. Table 2 depicts the major alternatives for solid-liquid filtration technology relevant to this study, and the rest of this section

Table 2

Filtration Alternatives and Maintenance Ratings

Mechanized Systems		Nonmechanized Systems	
Surface	Depth	Surface	Depth
Vacuum (2)	Gravity Filter	Screen Cloth (permanent) (2)	Pervious Dike (1)
Pressure (2)	Constant Rate (2)	Wood Chips (2)	Sandfill Weir (3)
Microscreen (3)	Constant Head (2)	Straw (2)	Straw (3)
Batch Screen (3)	Pressure Filter (2)	Gravel (2)	Wood Chips (3)
Diatomite (3)	Moving Bed Filter (3)		Slow Sand Filter (3)
Squeegee (belt press filter) (2)	Biflow Filter (2)		Gravel or Stone Filter (1)
	Upflow Filter (2)		Cartridge (2)

Note: Parenthetical numbers represent the following first-order approximations of maintenance requirements.

(1) Little or none
(2) Some
(3) Significant

is devoted to a discussion of this table. Categories are divided into mechanized versus nonmechanized systems and surface versus depth filtration. Mechanization may be achieved by wind, electrical, or hydro energy. Solar or chemical energy appears to be generally impractical for application to confined disposal area operation in the immediate future. The levels of maintenance and mechanization vary widely for the various categories listed in Table 2, and, for the range of slurry concentrations likely to be encountered in disposal area effluents, only limited information is available on the level of maintenance required; hence, the indicated estimates of these requirements represent relatively unsubstantiated first-order approximations.

Mechanized filter systems

17. Surface mechanized filters that may be candidates for dredged material dewatering or separation are vacuum filters, pressure filters, microscreens, and horizontal or vertical belt filter presses. Vacuum filters may be of three types: (a) rotary drums with an area of 50 to 500 sq ft; (b) continuous belts up to 3000 sq ft in filter area; and (c) rotary disks with diameters up to 15 ft. Design data for vacuum dewatering of materials similar to some dredged material are available from various sources; for example, Dickey (1961) provides information on yield and filtrate quality for clay and quartz slurries using various vacuum filter technologies. However, based on these process rates, on the order of 50 vacuum filter units would be required to handle the output of a small or medium-size (few acres) disposal area. Of course, a much larger containment area obviates the need for this type of filter, as discussed later.

18. Pressure filters, such as plate and frame filters, are widely used in dewatering organic and inorganic sludges, but they are high maintenance filters and would be rather impractical for dredged material processing, either on ship or shore. Microscreens have been employed in water treatment for many years, and attempts to clarify wastewaters or waters of highly variable solids content with microstrainers have recently yielded limited success (Lynam, Ettelt, and McAloon, 1969). This is not too surprising, since this technology was originally

designed to remove relatively large and structured solids, such as algae. However, microscreen units are designed with such porous septa (mesh size $> 20\mu$) that separation of the fine-grained clays in dredged material may be impossible. Operations employing non-mechanized filter cloths might overcome some of these problems by relatively rapid changes in the cloth media, and mechanized units in series could achieve similar results at a much higher capital cost.

19. Diatomite filters have been used in municipal technology since World War II to produce potable water, and they have also seen wide application in swimming pool clarification. The major disadvantage in the effective application of this technology to disposal area filtration systems is the continuous need to supply diatomaceous earth in proportion to the solids loading of the filtrate. With anticipated solids concentrations up to 10 g/ℓ, the cost of the body feed would be exorbitant.

20. The squeegee or belt filter press is a relatively new technology, with units manufactured in Europe (Alt, 1975) and the United States (Westinghouse, 1971). The Swiss-marketed Tower Belt Filter permits the adequate settling of coarse media-blinding particles prior to the compression cycles; whereas the Westinghouse Infilco squeegee depends on capillary dewatering of the suspension prior to squeezing water from the slurry as it passes along a continuous belt. Both units involve a substantially smaller capital investment than a vacuum filter system and probably pose fewer maintenance problems. Process rates are generally higher than vacuum filters, although it is difficult to achieve high cake solids contents with Squeegee or Tower Belt Filters. These units will be discussed more fully in Appendix D.

21. Mechanized depth filters, which are driven either by gravity or pressure, consist of fixed-bed or movable-bed media and operate in upflow, downflow, or horizontal flow modes. Each configuration has given rise to many innovations, and a large number of mechanized depth filtration systems are currently available.

22. Gravity filters of the constant rate type have been employed mainly for removing residual solids in the production of potable water.

Rate controllers have usually been used in the systems because surges or rapid changes in flow rate tend to upset the filtrate quality. However the assumed need for such rate control may be merely a matter of tradition dating back to the specification of 2 gpm/ft^2 for the first full-scale rapid sand filter in the United States. Cleasby (1972) points out how variable head and declining rate filters can in many cases produce satisfactory filtrates at lower unit costs.

23. Because of less sophisticated instrumentation, controls, piping, and other appurtenances, constant head filters have found wide use in tertiary wastewater treatment. They are well equipped to handle the more highly variable solids loading in wastewater flows; however, beyond a solids concentration of a few hundred milligrams per liter, the units clog quickly and require large volumes of backwash water. Pressure depth filters give longer runs and greater solids penetration than gravity filters, but this trade-off is offset by increased pumping costs.

24. Moving-bed filters have the advantage of presenting to the suspension a filter system that always has approximately the same flow resistance, since it is constantly being cleansed. The Simater ® (Water and Water Engineering, 1968) is a biflow filter design that has not been widely adopted in the United States, but a modification of this moving-bed filter might be attractive for filtering dredged material either with or without media recovery; unfortunately, however, the sole U.S. manufacturer has discontinued production of the unit.

25. Upflow filters show some real promise for filtering dredged materials. Since the flow passes from coarse to fine gradations in such filters, their solids holding capacity is markedly improved, even for suspensions with a high solids concentration. Steimle and Haney (1974) suggested that the reliability of such filters is even higher than conventional downflow designs.

<u>Nonmechanized filter systems</u>

26. Nonmechanized filter systems offer greater compatibility with current dredging disposal operations than do mechanized systems, if only because of their lower capital, maintenance, and operating costs. The effluent quality from such systems may or may not be lower than for

mechanized units.

27. Synthetic or natural media that are used as surface filters may provide solid-fluid separation, but generally not at a sufficiently high rate or without some maintenance. Candidate materials are synthetic cloths or thin layers of wood chips, straw, or gravel. The latter three materials have been used in erosion control, but would probably not be useful in the current context because such measures could only process a small volume of dredged material suspensions. Synthetic septa, such as commercial nonwoven cloths (Monsanto E2B and Celanese Mirafi), have been used in seepage and erosion control and as reinforcing to improve the bearing capacity of soil. Such cloths may actually behave as small depth filters in comparison to woven media, which respond well only to adequately flocculated suspensions under high hydraulic (pressure) gradients. A number of these woven and non-woven media were employed in the testing program outlined in Part III. In one instance (Charleston, South Carolina), a plastic filter cloth was incorporated into a full-scale dike. The basic difficulty in employing wood chips, straw, or gravel as surface filters is that the suspension particles have very little opportunity to make contact with the filter media, thereby resulting in a low overall efficiency or clarification.

28. Nonmechanized depth filters provide a series of strong candidates for an economic solution to the solid-liquid separation of dredged material; therefore, the major thrust of this research effort was directed toward the evaluation of pervious dikes, sandfill weirs, and gravel and sand filters. In addition, concepts such as slow sand filters and low maintenance filters of wood chips or straw were deemed worthy of consideration. Little, if any, information is available on rational design procedures for pervious dikes. The dikes constructed in the Buffalo and Cleveland Harbors were designed for structural integrity with virtually no attention being given to dredged material retention efficiency. If such dikes were properly designed, they should ideally become impervious about the time that the containment area is filled. So far, however, pervious dikes have only been designed as part of a harbor facility, and it has been difficult to determine their

retention capability.

29. The ability of pervious soils to retain the soluble and suspended components of wastewater has been reviewed in recent studies of the soil mantle as a wastewater treatment system. Except for bacteria and viruses, the migration of suspended material is of little concern in such systems, because fine-grained soils provide an effective filter medium. Pervious dikes would require significantly higher permeabilities than these soil filters because of the typically higher solids contents of the slurries to be treated. Sandfill weirs have been designed for diked disposal areas in the Milwaukee and Waukegan (Illinois) harbors, but the specifications for media size are not sufficiently detailed and the basis for estimating the design life of a given sand layer are not available from the design reports.

30. The use of straw or wood chips as a depth filter offers a fairly novel and meritous idea; straw is readily available and can be provided in compact form (bales) as a natural filter cell. No literature was identified to lend insight to this concept, but a few studies have indicated that straw or sawdust are good absorbents for oily water separation. One Environmental Protection Agency-supported study (EPA, 1970) examined the use of wood chips to filter spent Kraft liquor. Operating problems associated with straw, hay, or wood chips as filter media are the likelihood of producing highly colored effluents due to the leaching of humic substances from the media as it ages. This would seemingly add to maintenance and operation costs of these alternatives.

31. Slow sand filters have been employed to treat potable waters since antiquity. A simple design consists of essentially a trough filled with fine sand and fitted with a collecting underdrain. The operation may be intermittent, as in the case of wastewater treatment, whereby a resting period is provided for biological action to renew the clogged filter pores. Continuous flow systems are still employed routinely in many parts of the world to supply potable water. In reality, it might be better to state that the slow sand filter is actually a surface filter, because it removes the applied suspended load by biological action in a slime layer called a Smützdecke at the filter surface. In order to

provide enough contact time for biological action, flow rates are quite low (about 0.1 cm/sec), thereby necessitating large land areas for treatment. Slow sand filters have been employed to treat surface waters that contained no more than a few hundred milligrams of suspended solids per liter. Furthermore, if the applied suspension is too high in nonbiodegradable solids (as is the case in a dredged material slurry or a suspension with a high clay content), the filter would require high maintenance (e.g. raking to disturb the surface or scalping off the clogged layer).

32. Coarse media filters of gravel or stone have been designed to prevent the migration of soil fines while simultaneously allowing the free drainage of seeping water. In soil and hydraulics engineering these structures are known as protective filters, and empirically developed grain-size criteria (Terzaghi, 1922; Bertram, 1940; U.S. Army Corps of Engineers, Waterways Experiment Station, 1941, 1948 and 1953; U.S. Army Corps of Engineers Providence District, 1942; Terzaghi and Peck, 1967; and others) are employed to select the gradation of the filter materials. The thickness of such a filter is currently determined either by seepage analyses (Mallet and Pacquant, 1954; Creager, Justin, and Hinds, 1955; Cedergren, 1962) or by probability techniques (Kjellman, 1964; Silveira, 1965; Atmatzidis, 1973). Such filters could be employed as roughing filters to remove the coarse fraction of a dredging slurry and to protect the finer filters used to obtain higher effluent quality.

Characterization Study

33. The general lack of directly pertinent information on the dredged material characteristics that affect the design of a filtering system for disposal area effluents and the apparent absence of any data to evaluate the performance criteria of filtering systems under such conditions necessitated the conduct of an extensive experimental program during which a number of bottom sediments and disposal area effluents were characterized and various filter media were tested in the laboratory and at two locations in the field. The laboratory experimental

program was aimed at defining the effect of certain parameters on the filtration of disposal area supernatants; however, since the suspensions to be filtered were artificially prepared, a characterization study was first undertaken to (a) provide an understanding of the properties of dredged material that have a direct bearing on the required research for this project, (b) estimate the range of conditions under which effluent filtering systems would usually operate, and (c) define the range of conditions under which various filter media should be tested. This characterization study was based on data that were collected by (a) visits to Corps of Engineer offices around the country, (b) in situ and laboratory testing of samples taken during these visits, and (c) review of available pertinent literature.

34. Thirty-two samples from locations in and around dredged material confinement areas were collected during visits to Corps of Engineer District and Field Offices. All samples are listed and described briefly in Table 3, and the solids content of each sample is presented in Table 4. Grain-size distributions of dredged material, sediments near effluent weirs, and suspended solids in disposal area effluents are given in Figures 1, 2, and 3, respectively.

35. A uniform and consistent notation system was adopted to quickly and easily identify the nature of each sample, its geographic location, and the approximate time of sampling. A typical sample designation consists of three identifiers. The first identifier is a pair of letters that designate the city and state from which the sample was taken; the second is a chronological number that designates the time and sample group; and the third is a letter that defines the sample type according to the following scheme:

S - Supernatant in disposal area

M - Mixing zone water behind weir or filter system

A - Ambient water

T - Top 2 cm of sediment in disposal area

P - Pipeline slurry being pumped into disposal area

B - Bottom sediments that are from candidate areas for dredging

36. Dredged material characteristics can be identified in terms

Table 3

List of Samples

Sample	Location	Description
PP1S	Philadelphia, Pa.	Supernatant discharged from disposal area
PP1A	Philadelphia, Pa.	Ambient water
PP1P	Philadelphia, Pa.	Dredged material pumped into disposal area
SW2S	Seattle, Wash.	Supernatant discharged from disposal area
SW2A	Seattle, Wash.	Ambient water
SW2P	Seattle, Wash.	Dredged material pumped into disposal area
SC3T	Sacramento, Cal.	Top sediments near overflow weir
TO4A	Toledo, Ohio	Ambient water
TO4B	Toledo, Ohio	Bottom sediments; candidates for dredging
TO4T	Toledo, Ohio	Top sediments near overflow weir
NV5S	Norfolk, Va.	Supernatant discharged from disposal area
NV5M	Norfolk, Va.	Water from mixing zone behind weir
NV5A	Norfolk, Va.	Ambient water
NV5T	Norfolk, Va.	Top sediments near overflow weir
WN6S	Wilmington, N.C.	Supernatant discharged from disposal area
WN6A	Wilmington, N.C.	Ambient water
WN6P	Wilmington, N.C.	Dredged material pumped into disposal area
CS7S	Charleston, S.C.	Supernatant discharged from disposal area
CS7M	Charleston, S.C.	Water from mixing zone behind weir
CS7A	Charleston, S.C.	Ambient water
CS7P	Charleston, S.C.	Dredged material pumped into disposal area
SG8S	Savannah, Ga.	Supernatant discharged from disposal area
SG8M	Savannah, Ga.	Water from mixing zone behind weir
SG8P	Savannah, Ga.	Dredged material pumped into disposal area
SG8T	Savannah, Ga.	Top sediments near overflow weir
JF9S	Jacksonville, Fla.	Supernatant discharged from disposal area
JF9P	Jacksonville, Fla.	Dredged material pumped into disposal area
JF9T	Jacksonville, Fla.	Top sediments 300 feet from overflow weir
GT10B	Galveston, Texas	Bottom sediments; candidates for dredging
TO11P	Toledo, Ohio	Dredged material pumped into disposal area
TO11S	Toledo, Ohio	Supernatant discharged from disposal area

Table 4

Solids Content Determinations

Sample	Total Solids (%)	Dissolved Solids (%)	Suspended Solids (%)	Volatile Solids (%)	Dissolved Volatile Solids (%)	Suspended Volatile Solids (%)
PP1S	0.09	0.06	0.03	0.02	0.02	ND
PP1A	0.19	0.19	ND	0.03	0.03	ND
PP1P	11.93	0.26	11.67	0.11	0.05	0.06
SW2S	3.09	3.02	0.07	0.53	0.53	ND
SW2A	2.28	2.28	ND	0.39	0.39	ND
SW2P	14.97	2.23	12.74	1.30	0.43	0.87
SC3Ta	38.14	—	—	3.02	—	—
SC3Tb	87.93	—	—	2.75	—	—
TO4A	0.04	0.04	ND	0.01	0.01	ND
TO4B	28.87	0.07	28.80	3.13	3.06	3.07
TO4T	61.44	—	—	7.43	—	—
NV5S	1.56	1.54	0.02	0.26	0.26	ND
NV5M	1.57	1.52	0.05	0.27	0.24	0.03
NV5A	1.77	1.69	0.08	0.34	0.29	0.05
NV5T	36.12	—	—	3.86	—	—
WN6S	1.20	1.06	0.14	0.20	0.15	0.05
WN6A	0.82	0.74	0.08	0.14	0.14	ND
WN6P	11.05	1.72	9.33	1.99	0.28	1.71
CS7S	0.71	0.64	0.07	0.11	0.11	ND
CS7M	0.50	0.46	0.04	0.08	0.08	ND
CS7A	0.34	0.14	0.20	0.06	0.05	0.01
CS7P	10.79	2.36	8.43	1.33	0.44	0.89
SG8S	3.06	2.91	0.15	0.38	0.33	0.05
SG8M	2.89	2.76	0.13	0.38	0.33	0.05
SG8P	6.27	2.66	3.61	1.09	0.48	0.61
SG8T	53.57	—	—	7.43	—	—
JF9S	2.18	2.02	0.16	0.34	0.27	0.07
JF9P	12.22	1.63	10.59	1.97	0.25	1.72
JF9T	62.02	—	—	6.92	—	—
GT10B	26.42	2.17	24.25	2.15	0.34	1.81
TO11P	12.69	0.04	12.65	1.15	0.03	1.12
TO11S	0.08	0.04	ND	0.04	0.04	ND

Notes:
1. All data are determined on a wet weight basis.
2. ND designates "not detectable".
3. Dashes indicate that results could not be obtained because of the nature of the sample.

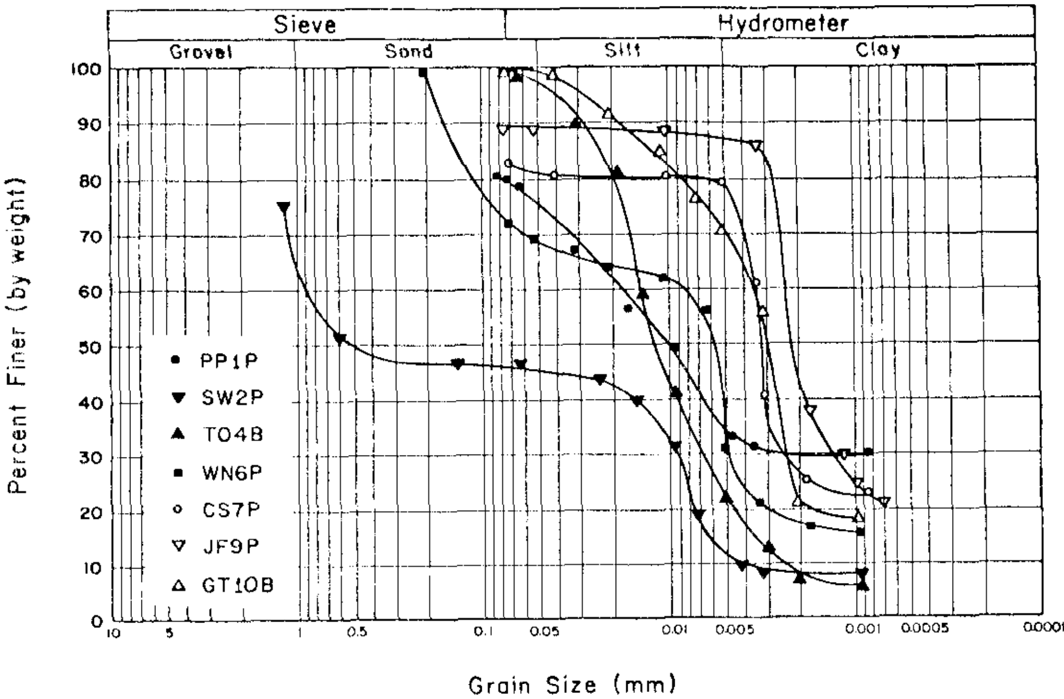

Figure 1. Grain-Size Distributions of Dredged Material

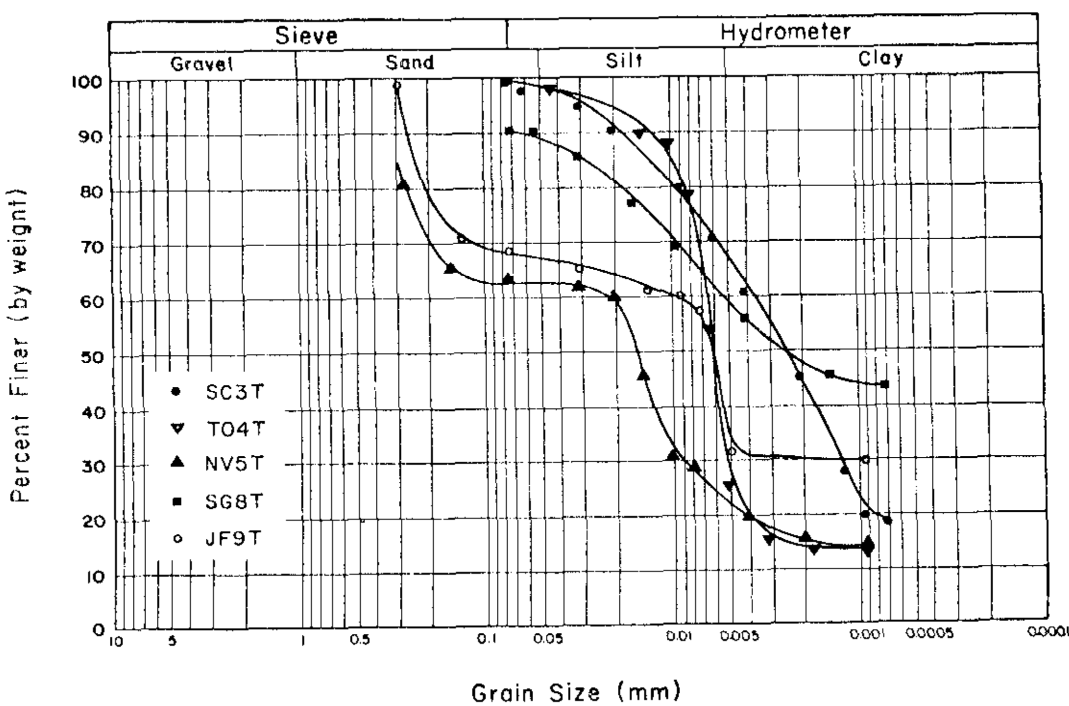

Figure 2. Grain-Size Distributions of Sediments near Effluent Weirs

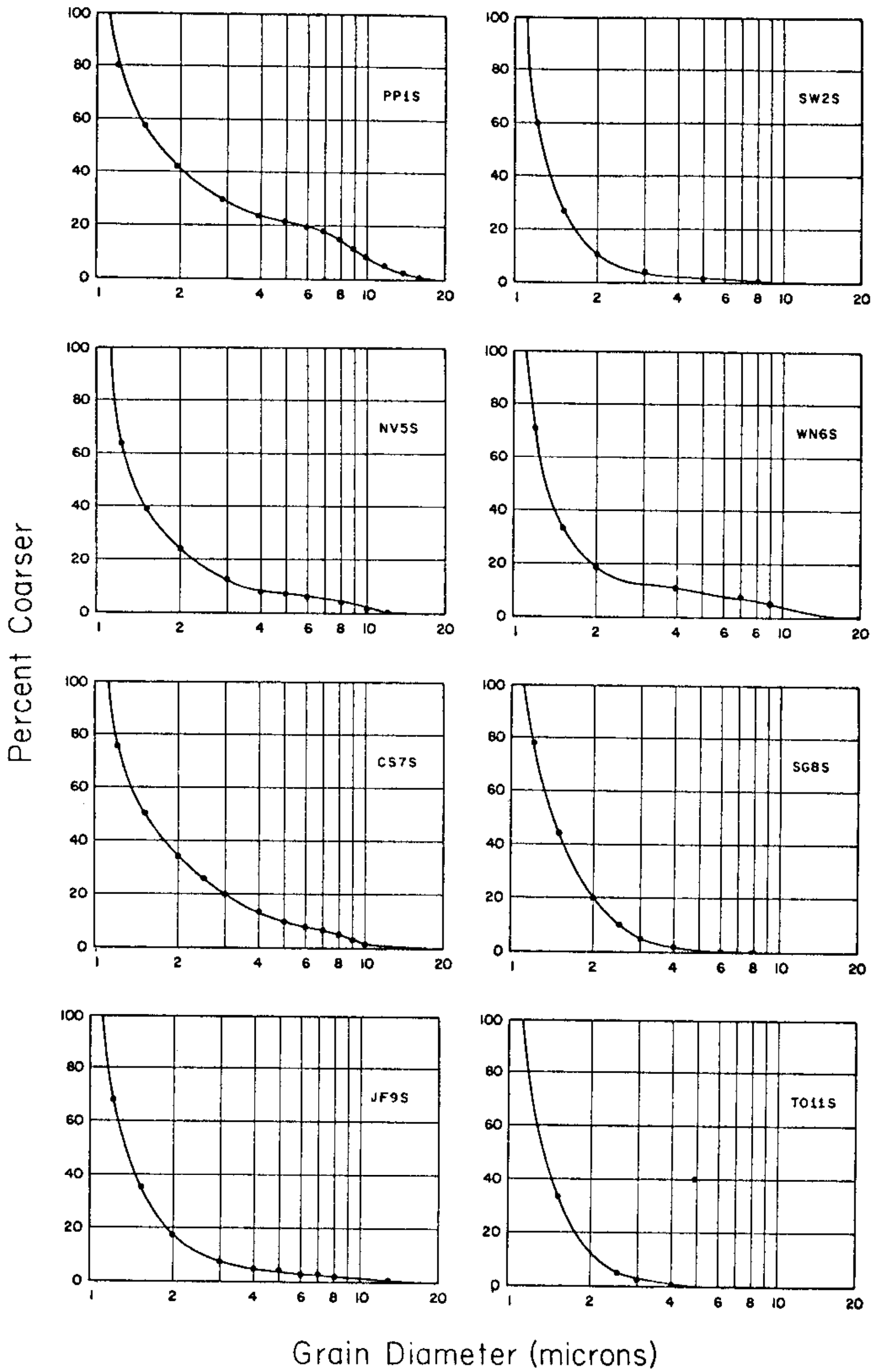

Figure 3. Grain-Size Distributions of Suspended Solids in Disposal Area Effluents

of physical engineering, and chemical properties (Boyd et al., 1972). Some data on the characteristics of dredged material were provided in a study of the Great Lakes (U. S. Army Corps of Engineers, Buffalo District, 1969) and in a study of the Delaware River (U. S. Army Corps of Engineers, Philadelphia District, 1969), but such data for other areas are either not available or not easily accessible. The data collected and reported herein serve to identify the chemical constituents of bottom sediments and the grain-size distributions of bottom sediments and disposal area effluents and supernatants; also included is some information on the sedimentation of solids in disposal areas.

Chemical constituents of bottom sediments

37. Bottom sediments contain constituents that exist in different chemical forms and are found in various concentrations at different locations within the layer to be dredged; in addition, regional variations are often extremely broad (U. S. Army Corps of Engineers, New Orleans District, 1973; Keeley and Engler, 1974). The chemical properties of bottom sediments that are in areas that are candidates for dredging are of twofold importance because (a) they have a direct bearing on the physical and engineering properties of the dredged material, and (b) they may influence the acceptability of depositing the dredged material in open water. In an effort to minimize the effects of depositing polluted dredged material in the open waters, the Environmental Protection Agency had issued regulatory criteria (EPA, 1973; Keeley and Engler, 1974). These criteria were recently (EPA, 1975a) superseded by more comprehensive guidelines.

38. Data on sediment chemistry have been collected for about fifty locations in the United States, and values for the seven parameters included in the old EPA criteria are given in Appendix A. For every location the range and average value of each constituent are given. The number of samples for each location ranged from one to more than one hundred, but generally was on the order of five to twenty. For each location mean values were calculated for each parameter, and frequency and cumulative distributions are presented in Figure A1.

Grain-size distribution
of bottom sediments

39. The grain-size distribution of dredged material is one of the important physical properties that, among other factors, determine the amount of turbidity associated with disposal operations and the rate of solids sedimentation. Coarse-grained dredged material usually does not cause problems in dredging operations and generally yields disposal area effluents of acceptable quality.

40. The data reported herein are for fine-grained bottom sediments and were obtained for sixty locations around the country. The number of samples from each location ranged from two to more than one hundred, but generally was on the order of five to fifteen. The data required to reproduce the average grain-size distribution curve for each location are reported in Appendix A, together with the statistical distribution of certain size fractions of the bottom sediments (Figure A 2).

41. Submicron particles constitute a large portion (up to one-half by weight) of the bottom sediments that are candidates for dredging. For two-thirds of the locations, the amount of submicron particles ranges between 10 and 40 percent by weight. Particles of this size, unless they aggregate to form larger equivalent particles, will not settle out of suspension, even with long detention times provided by a large disposal area.

42. At this point it is of great significance to note that all data on the grain size distributions reported in Appendix A were obtained by using the standard ASTM procedures for hydrometer tests, which involves the use of a dispersing agent (sodium hexametaphosphate). Since the addition of a dispersing agent to the dredged material disaggregates flocculated clay particles, the resulting grain-size distributions are not representative of the true particle sizes of the materials that are pumped into a disposal area and they do not reflect the actual hydrodynamic behavior of the sediments. This has been substantiated by a number of tests conducted both with and without dispersing agent on samples of dredged material that were candidates for dredging or samples taken from the inflow pipes to various disposal

areas throughout the country, and some typical results are shown in Figure 4. For the materials tested, particles smaller than 10μ are found to constitute 15 to 35 percent of the sample when no dispersing agent was used and 30 to 90 percent when a dispersing agent was used; submicron particles constitute 3 to 15 percent of the samples tested in its natural state and 7 to 40 percent of a dispersed sample.

Disposal area effluents and supernatants

43. The available literature provides extremely limited information on the suspended solids content of effluents from disposal areas or of supernatant waters in the disposal area at various distances from the inflow pipe. In order to estimate the range of conditions under which effluent filtering systems will usually operate, the variations in the two parameters that affect the nature of the effluent (namely, the concentration and grain-size distribution of the suspended solids) must be determined. Table 5 presents the solids content of disposal area effluents collected from facilities around the United States. Total suspended solids vary from about 200 to 1600 mg/ℓ, and total suspended nonvolatile solids range from about 200 to 1000 mg/ℓ; however, the Sacramento District reported suspended solids ranging from 80 to 137 mg/ℓ for one of their disposal areas (U. S. Army Corps of Engineers, Sacramento District, 1974). For a number of other cases of dredging in a freshwater environment (U. S. Army Corps of Engineers, South Pacific Division, 1972 and 1973), the amount of total solids in the disposal area effluents ranged from about 500 to 1000 mg/ℓ. The grain-size distributions of the suspended solids in the effluents listed in Table 5 are shown in Figure 3. When interpreting these data, it must be recognized that (a) the indicated lower limit of particle sizes (about 1μ) is not necessarily the actual lower limit, but it is the practical detection limit of the Coulter counter employed and (b) a substantial portion of particles in the 5 to 20μ range can be attributed to the existence of suspended volatile solids.

Sedimentation in disposal areas

44. A large number of factors affect the sedimentation of solids

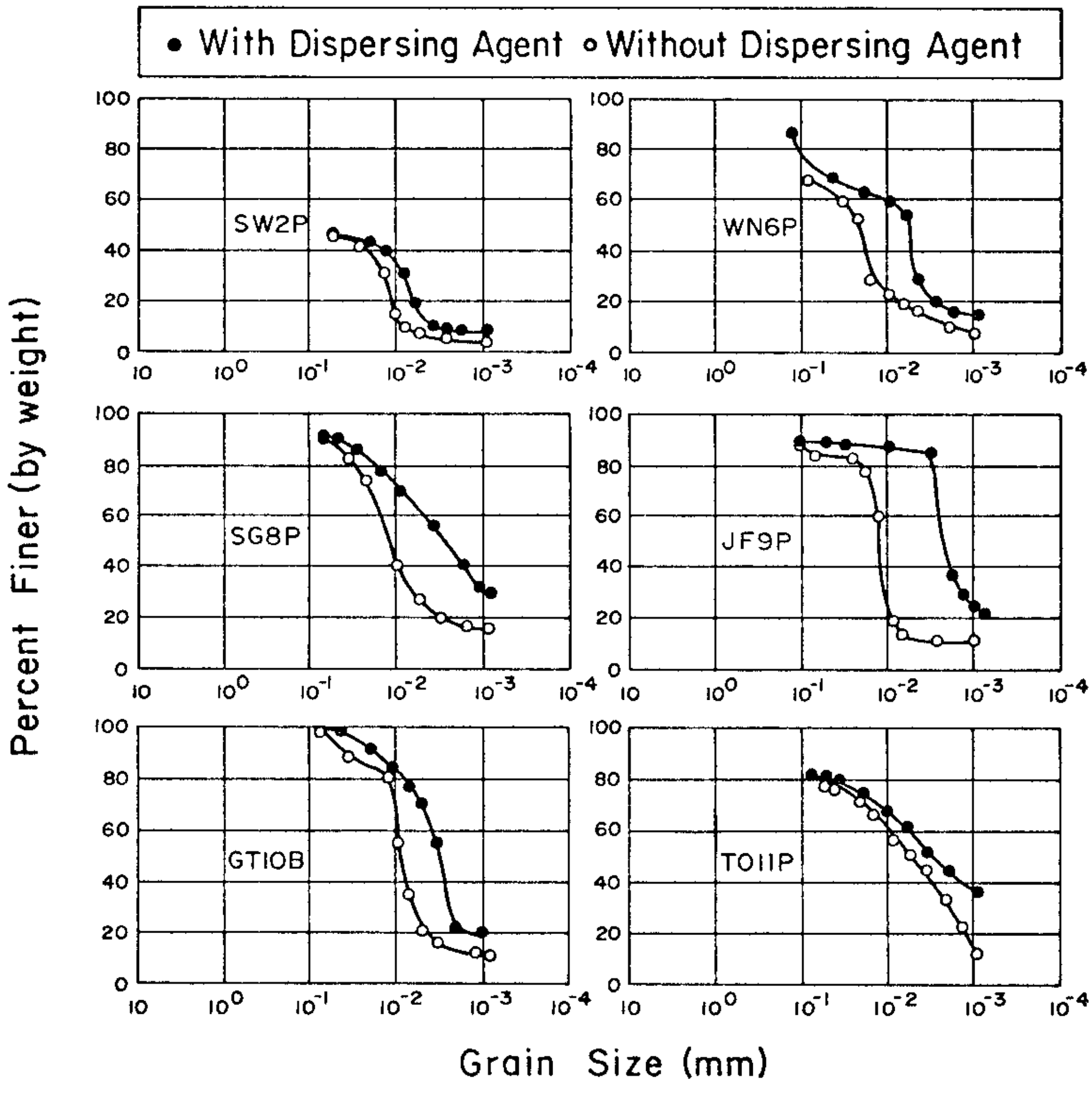

Figure 4. Grain-Size Distributions of Dredged Material Determined With and Without Dispersing Agent

Table 5

Solids Content of Disposal Area Effluents

Sample Number	Total Solids (mg/ℓ)	Total Suspended Solids (mg/ℓ)	Total Suspended Nonvolatile Solids (mg/ℓ)
PP1S	853	221	221
SW2S	30,850	661	639
NV5S	15,643	240	240
WN6S	12,026	1446	968
CS7S	7,083	716	701
SG8S	30,647	1512	984
JF9S	21,818	1592	866
TO11S	795	~0	~0

in disposal areas; the most important of these are (a) the size and shape of the disposal area, (b) the relative location of the inflow pipe and the sluicing device, (c) the detention time, (d) channelization, (e) wind, and (f) vegetation. Large-size disposal areas permit the storage of large quantities of slurry, and they usually provide sufficient detention time to allow most of the solids to settle from the supernatant waters before they are retured to the receiving waters. Small-size disposal areas, on the other hand, do not have this advantage, and simple sedimentation may not provide effluents of acceptable quality.

45. In addition, channelization (which may be caused by the mounding of coarse material near the inflow pipe, adverse topography inside the disposal area, or the placement of the inflow pipe too close to the sluicing device) effectively decreases the retention time because only part of the disposal area is used as a sedimentation basin and thereby the sedimentation rate is reduced due to higher horizontal flow velocities. Strong winds may agitate the otherwise quiescent settling zones and cause slower net settling velocities and/or resuspension of material that has already settled. Vegetation may aid in the cleansing process by decreasing high flow velocities and providing quiescent pools where effective sedimentation can occur; vegetation may also act as a coarser filter.

46. The materials that settle out of suspension rapidly near the inflow pipe range from sand to cobbles. In addition, portions of the clay fraction of the dredged material are quickly removed either in the form of clay balls or by virtue of the prior attachment of clay particles to larger particles. However, such phenomena can not be relied upon to effectively remove fine suspended particles by gravity sedimentation and, under certain adverse conditions, the water reaching a sluice may carry a high load of suspended solids.

Previous Research on the Filtration of Clay Suspensions

47. The filtration of clay suspensions can be generally considered as either clarification of dilute suspensions or dewatering of

slurries. The latter category has been mentioned earlier in this chapter in conjunction with the mineral-processing industry; in general, there is available in this case some experience and information on the alternative techniques for dewatering slurries, and the performance of specified systems can be predicted with reasonable confidence. On the other hand, the clarification of dilute suspensions varies considerably under seemingly similar conditions, and resulting designs are largely empirical and based frequently on a trial-and-error approach. Since clarification of dilute clay suspensions is an important objective of this research effort, a review of available information on this subject was deemed appropriate.

48. In a recent review of experimental investigations concerned with deep bed filtration, Wright, Kavanaugh, and Pearson (1970) divided published data into three basic categories based on the nature of the particulate suspensions encountered or employed (inorganic, organic, or synthetic). Although information on the filtration of clay suspensions is of major importance to the present study, such information is rather limited and the reported investigations have not covered the parameter ranges of interest in this work. Table 6 lists the ranges of parameters that were covered in various experimental studies of clay filtration; the data presented in this table were extracted from individual publications and/or summaries presented by Herzig, LeClerc, and LeGoff (1970); Wright, Kavanaugh, and Pearson (1970); and FitzPatrick (1972). Dash entries in the table indicate that information could not be ascertained from the data available. An examination of Table 6 leads to the following observations regarding previous research on the filtration of clay suspensions:

- a. The equivalent diameter of the suspended clay varied from about 0.5 to 40μ.
- b. Concentrations of suspended solids were generally not more than 200 mg/ℓ and often as low as 5 mg/ℓ.
- c. Initial discharge velocities varied over a wide range (0.007 to 3 cm/sec), the lower velocities being associated with a slow sand filter and the higher velocities with a rapid sand filter.

Table 6

Summary of Previous Work on Filtration of Clay Suspensions

Investigator	Filter Medium			Suspended Solids			Initial Discharge Velocity (cm/sec)	Chemical Additive
	Type	Size (mm)	Porosity	Type	Size (microns)	Concentration (mg/ℓ)		
Agrawal (1966)	Sand Anthracite	0.2-0.8	0.41-0.68	Bentonite	1-30	5-100	0.13-0.34	Flocculant
Cleasby (1969)	Sand	0.71	0.40	Kaolinite	1-25	7-20	0.41	Flocculant
Deb (1969)	Sand	0.65-0.77	0.43	Fuller's Earth	6	100	0.13-0.20	None
Edwards and Monke (1967)	Sand	0.35	—	Clay	1	—	0.007	Ions
Ghosh (1958)	Sand Glass Spheres	0.46-0.77	0.37-0.41	Fuller's Earth	20	50-200	1-3	None
Hunter and Alexander (1963)	Sand	—	—	Kaolinite	0.55	—	—	—
Ison (1967)	Sand	0.46-0.78	0.38	Kaolinite	2-9	100	0.13-0.19	None
Ives (1961)	Sand Anthracite	0.25-1.30	—	Kaolinite	2.5-10	—	0.05-0.25	None
Iwasaki (1937)	Sand	0.10-0.80	0.40	Clay	1-40	—	0.0035-0.012	None
Jorden (1963)	Gravel	5.50	—	Clay	1	150	0.007	Ions
Mintz and Krishtul (1960)	Sand	1.0-2.15	—	Clay	—	—	0.15-0.25	None or Flocculant
Smith (1967)	Sand	0.60	—	Bentonite	5	5-6	0.14	Flocculant or Salt
Trzaska (1966)	Glass Spheres	0.80-1.30	—	Clay	2	—	0.007-0.025	None

Note: Dashes indicate that information was not reported or could not be obtained.

d. Sand has been the usual filter medium although glass spheres or gravel have sometimes been used.

e. The equivalent grain diameter of the sands and glass spheres ranged from 0.1 to 2.2 mm, and the porosity of most filter beds was about 0.4, which is expected from rounded sands and gravels, as well as glass spheres.

f. Very often a flocculant or ions were added to the suspension before filtration to enhance particle agglomeration or attachment within the filter.

49. Since most investigations were aimed at clarifying surface water for municipal or industrial supply, it is not surprising that concentrations of clay in the filter suspensions rarely exceeded 100 mg/ℓ; this is the range for which deep bed filters function well and are amenable to automation in operation. Certainly these low levels of suspended solids do not lend themselves to surface filtration. For dredged material disposal operations, supernatants with suspended solids on the order of those reported in Table 6 (< 200 mg/ℓ) would probably require little, if any, treatment, and therefore the information in Table 6 is not of direct applicability to the problem at hand (i.e. designing granular media filters to handle much more concentrated (up to several grams per liter) suspensions of dominantly clay particles). However, this lack of available information served as the major impetus for the extensive laboratory test program described in Part III.

Summary

50. Recently imposed guidelines require a case-by-case evaluation of discharges from dredged material confinement facilities to ascertain that established water quality standards are satisfied. A manual that is currently in preparation will define the procedures necessary to evaluate such discharges. In the past, criteria for determining effluent quality were not standardized; according to those criteria, disposal areas were required to have a suspended solids retention efficiency that ranged from as low as 80 to more than 99 percent (actually 99.99 percent). Efforts to control effluent quality have been limited, and the procedures were mainly empirical; there appears to exist no documented methodology

for the control of effluent quality. However, until bottom sediment quality improves substantially, the number of open-water disposal operations is likely to decrease in favor of confined disposal for dredged material.

51. The grain-size distributions of dredged material vary considerably, both locally and regionally. Suspended particle size is an important, if not dominant, parameter in determining the efficiency of a confined disposal area; soil particles smaller than 10μ constitute a large portion of dredged material, and these particles can definitely cause problems in the quality of the effluents from disposal areas.

52. Existing dredged material confinement facilities usually allow detention times that are adequate to reduce the concentration of suspended solids in the effluents to a range between less than 0.1 g/ℓ and about 1 to 2 g/ℓ; therefore, retention efficiencies much higher than 90 percent are being realized at most sites. The development of new concepts in the disposal of dredged material may lead to the use of small capacity transfer areas in the near future; because of small detention times, the effluents from such areas, if untreated, would have loads of suspended solids much higher than those experienced today.

53. The performance of conventional filter systems for dewatering clay slurries can be predicted with reasonable confidence on the basis of existing information and experience. However, available information on deep bed filtration of dilute clay suspensions is of limited applicability to the problem of clarifying disposal area supernatants.

54. The necessity to develop concepts for designing filter systems (such as pervious dikes and sandfill weirs) to treat disposal area supernatants becomes more urgent with time; such systems must simultaneously control the amount of suspended solids in the effluent and allow fast drainage of the disposal area. Filter systems for disposal area supernatants should be able to effectively function under (a) either a freshwater or saline environment, (b) a concentration of suspended solids ranging from as low as 0.1 g/ℓ to perhaps more than 10 g/ℓ, and (c) suspended particle sizes less than 10 to 20μ.

PART III: EXPERIMENTAL PROGRAM

55. The background information presented in Part II and the general lack of data on the filterability of suspensions similar to those that occur in confinement areas for dredged material emphasize the need for a thorough experimental investigation of filter media that might be used as components of filtering systems for disposal area supernatants. Although initial considerations suggest that this need be satisfied by conducting a series of field filtration tests with actual disposal area supernatants, in situ tests have the disadvantages that (a) a large number of disposal areas must be investigated to ensure that a sufficiently broad and representative range of supernatants has been examined; (b) various logistics problems and adverse weather conditions must be overcome; (c) test schedules must be compatible with dredging schedules; (d) the concentrations of suspended solids in the filter suspensions cannot be controlled; and (e) it is virtually impossible to conduct the large number of specialized tests that are needed to characterize the influent and effluent samples properly. On the other hand, laboratory tests have the advantages that (a) test conditions are relatively controllable and the quality of the filter suspensions can be predetermined with a good degree of reliability; (b) appropriate analyses (e.g. grain-size distributions, mass concentrations, etc.) on influent and effluent samples can be readily conducted; (c) convenience is enjoyed; and (d) the application of the Scientific Method is facilitated.

56. Nothwithstanding the advantages, laboratory tests have the disadvantage that properly scaled filter columns with realistic filter media require large quantities of filtrate to achieve adequate measures of their clogging tendencies, and the acquisition and preservation of such large quantities of disposal area supernatants is a practically impossible task. One major difficulty associated with any short-term experimental study, regardless of whether field or laboratory tests are involved, is concerned with the extrapolation of the test data to predict the response for longer periods of time; this is an inherent shortcoming in any experimental program, but it is particularly significant for the study undertaken.

57. A careful consideration of the foregoing advantages and disadvantages, together with (a) an enumeration of the variables to be investigated, (b) an estimate of the number of tests required, and (c) an assessment of the time available, led to the decision to direct the major effort in this study to the conduct of laboratory filtration tests. However, similar experimental equipment and techniques were used to perform two series of field filtration tests, one in a freshwater environment and the other in a saltwater environment. These tests were conducted in order to complement the extensive series of laboratory tests and to provide data whereby variations in the performance of filter media under laboratory and field tests might be assessed and guidance might be obtained for extending the findings of the laboratory tests to the design of filter systems for disposal area supernatants.

58. Described herein are (a) the various test series that were conducted, (b) the filter media that were investigated, (c) the test parameters that were measured and the ranges that were selected, (d) the rationale behind the experimental plan, (e) the equipment and techniques that were employed for each test, and (f) the data-collection procedures.

Laboratory Filtration Tests

59. Approximately two hundred and fifty laboratory filtration tests were conducted to determine the performance capabilities of several different granular and fibrous filter media under a variety of simulated field conditions. The selection of filter media, test variables, and quantitative values for these variables was governed to a large extent by field performance requirements and the expected range of operating conditions.

60. Eight different granular filter media were selected according to type (sand, gravel, and anthracite) and grain size (effective grain size ranged from approximately 0.4 to 5.0 mm). Seven different fibrous media were selected according to basic material (synthetic or metal fibers), mesh size (5 to 50μ), and weave pattern (random or regular). Artificial suspensions with suspended solids (primarily kaolinite or

illite clays) concentrations that varied from 0.1 to 10 g/ℓ were prepared in either fresh or saline (ionic strength from 0.001 to 0.3) water. A filter depth (up to 8 ft), flow direction (downflow, upflow, or horizontal), and initial flow rate (0.06 to 0.65 cm/sec) were specified for each test. The values assigned to some of the variables were selected so that extreme rather than intermediate operating conditions were investigated with the understanding that the data obtained could be interpolated with the benefit of theoretical insight to estimate behavior for intermediate operating conditions.

61. A limited number of tests were conducted to (a) estimate the effect of suspended organic matter on filter performance, (b) assess the behavior of granular filter media under upflow and intermittent operating conditions, (c) investigate the possibility of using nonconventional materials (such as straw, wood chips, and sawdust) as filter media, (d) evaluate on a comparative basis the effectiveness of vacuum filtration equipment for dewatering dredged material slurries, and (e) examine the backwashing efficiency of selected granular media.

Materials and methods

62. The planning and execution of the laboratory test program involved (a) the development of a methodology for producing suspensions that simulate disposal area effluents, (b) the selection of appropriate filter media, (c) the design and construction of equipment, and (d) the adoption and implementation of methods to analyze filtrate samples.

63. Suspensions. The suspended solids in the influent suspensions for the laboratory filtration tests consisted of commercially available clay soils of two different types: kaolinite and illite (Grundite). The kaolinite was a water-processed hydrated aluminum silicate clay known as Hydrite-R marketed by the Georgia Kaolin Company of Elizabeth, New Jersey; the illite was the principal clay mineral in a clay soil marketed under the name Grundite by the Illinois Clay Products of Joliet, Illinois. These commercially available clays (both of which possess low levels of soluble salts and are essentially inert chemically) satisfactorily covered the range of grain sizes encountered in many disposal area effluents; as shown in Figure 5, the grain-size distributions of

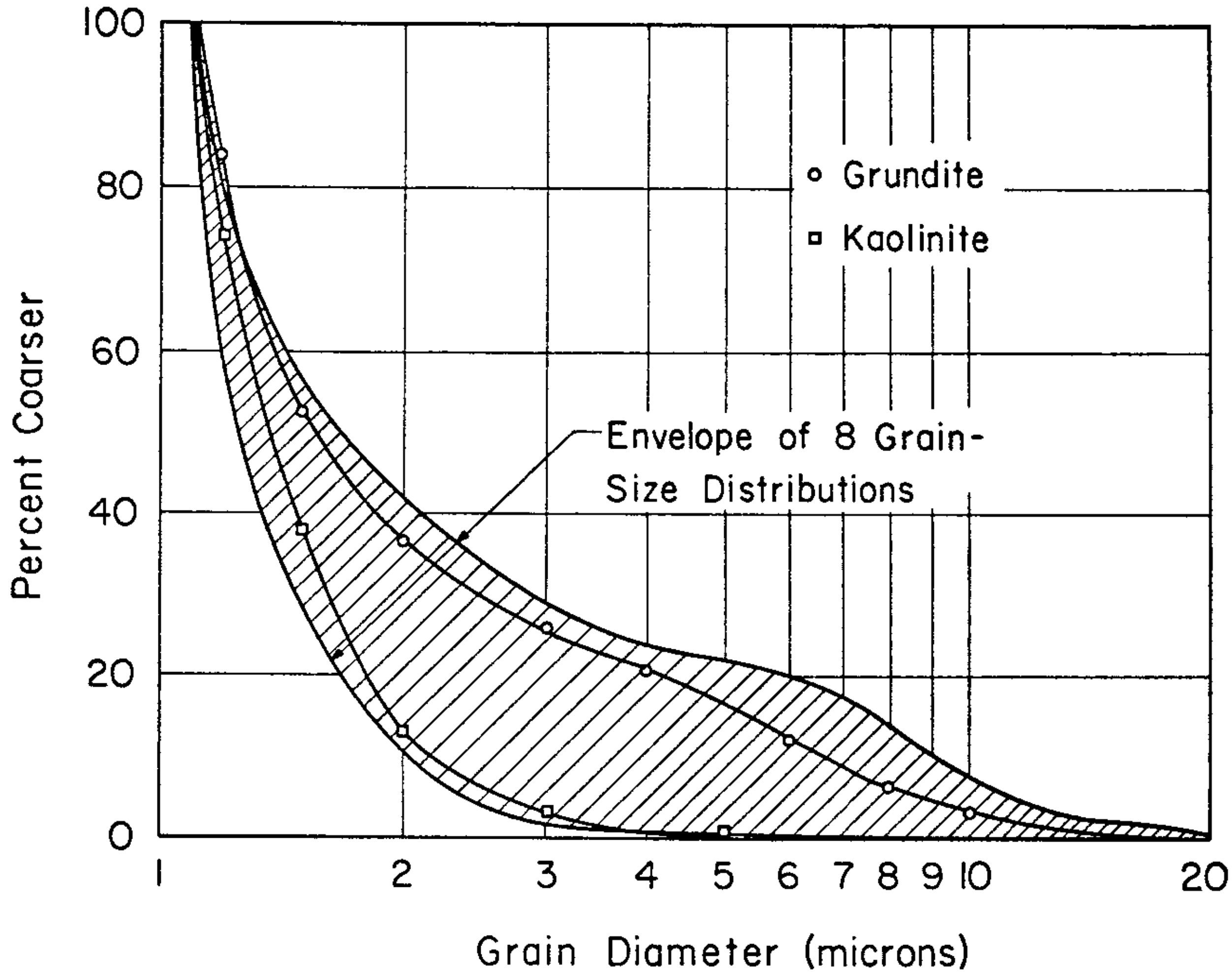

Figure 5. Comparison of Grain-Size Distributions of Clay Minerals Used in this Study and Suspended Solids in Disposal Area Effluents.

these two clays lie within the envelope of grain-size distributions of suspended solids found in disposal area effluents (see Figure 3 for individual curves). The range of grain diameters (1 to 20μ) plotted in Figure 5 was the Coulter counter detection range selected for these materials; accurate counting and sizing for diameters less than 1μ is virtually impossible without the use of a considerably more involved technique. The grain-size distributions of Grundite and kaolinite are superimposed in Figure 6 on the envelope of the average grain-size distributions of bottom sediments from 60 locations around the United States and in Figure 7 on the envelope of grain-size distributions of dredged materials from 10 locations in the United States.

64. Complete data on bottom sediments are presented in Appendix A, and most of the gradation curves of the dredged materials are given in Figure 4. The gradation curves in Figure 7 were obtained on the material passing a No. 200 sieve (0.074 mm) without using a dispersing agent when conducting the hydrometer test. Hence, the grain-size distributions of the clays chosen for the laboratory filtration tests are reasonably representative of the grain-size distributions suspended in many disposal area effluents that might logically pass through a filter system.

65. To account for the situation that might be encountered in small disposal areas where limited sedimentation times are available, a wide range was chosen for the concentration of suspended solids (0.1, 1, 5, or 10 g/ℓ for tests with granular media, and 1 or 10 g/ℓ for tests with fibrous media).

66. Filter media. Eight different materials were selected for use as granular filter media. The characteristics, descriptions, and grain-size distributions of these materials are given in Table 7 and Figure 8. Since the dependence of filter performance on grain diameter is very strong for granular media, a wide range of effective grain sizes ($0.38 \text{ mm} < D_{10} < 5.0 \text{ mm}$) was selected. All eight materials were tested as single-layer filter media, and five were used in the various dual-layer combinations described in Table 8.

67. After a preliminary evaluation of the performance of single-layer granular media was completed, the dual-layer filters were selected

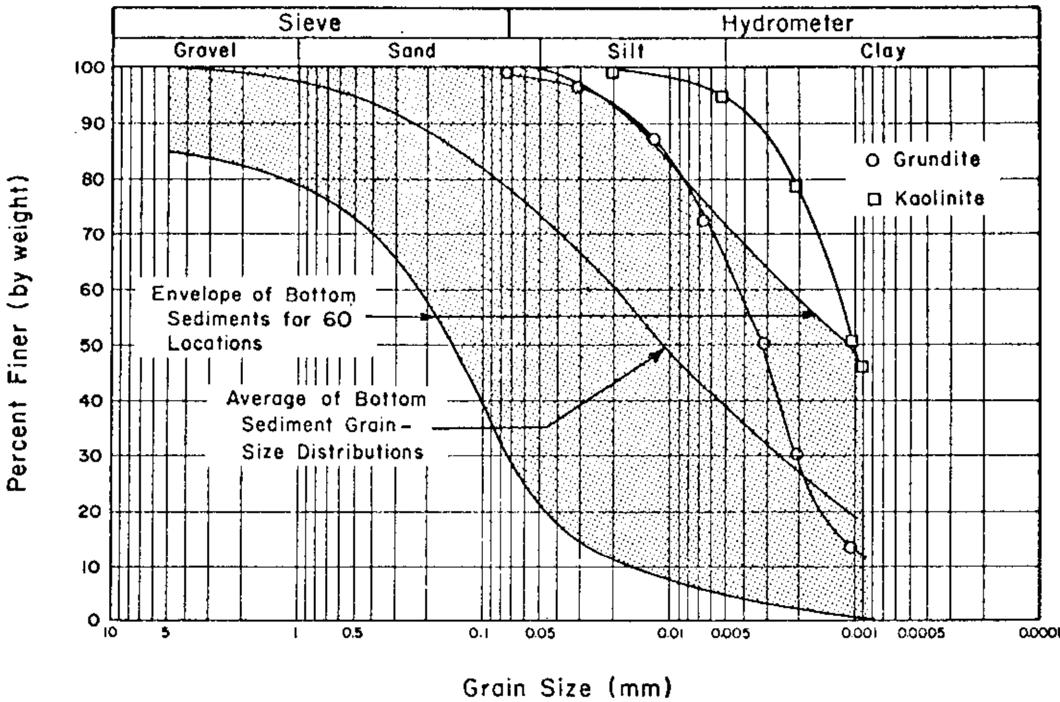

Figure 6. Grain-Size Distributions of Grundite and Kaolinite and Envelope of Average Grain Size Distribution of Bottom Sediments from Sixty Locations

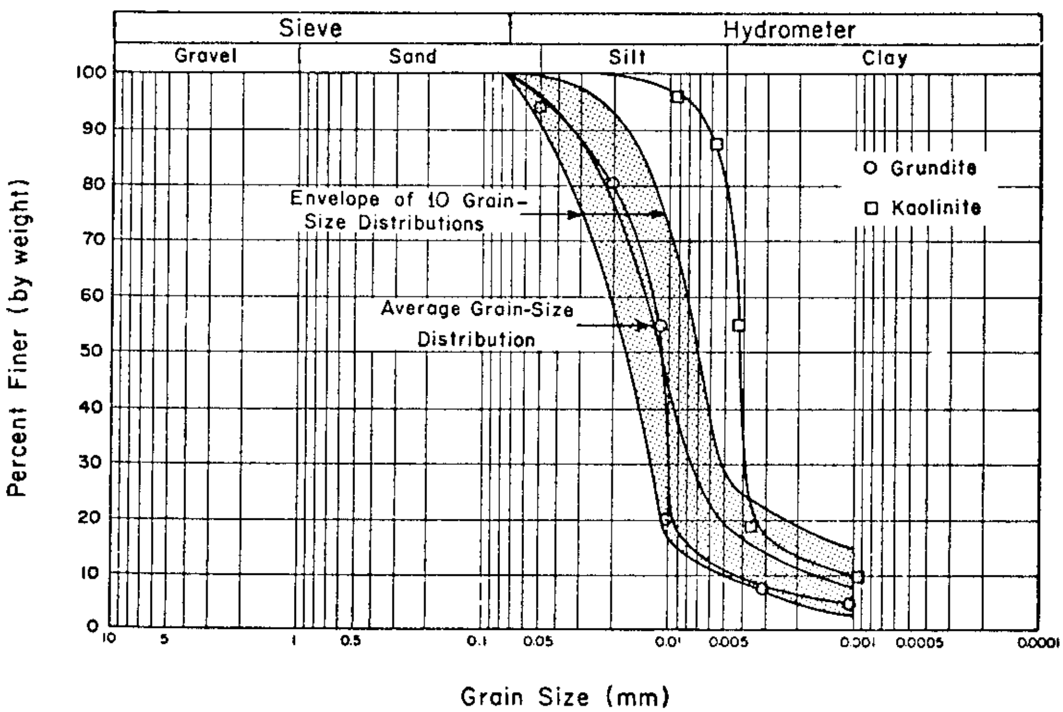

Figure 7. Grain-Size Distributions of Grundite and Kaolinite and Envelope of Grain-Size Distributions of Dredged Material from Ten Locations

Table 7

Characteristics of Granular Filter Media

Medium Identification Number	Effective Particle Size d_{10} (mm)	Uniformity Coefficient $C_u = d_{60}/d_{10}$	Description
1	0.38	1.44	Fine sand (FS)
2	1.00	1.30	Coarse sand (CS)
3	2.00	2.00	Fine gravel (FG)
4	5.00	1.40	Coarse gravel (CG)
5	1.00	5.00	Sand-gravel mix (SG)
6	0.85	1.40	Fine anthracite (FA)
7	1.80	1.66	Medium anthracite (MA)
8	3.80	1.49	Coarse anthracite (CA)

Table 8

Components of Dual-Layer Granular Filter Media

Medium Identification Number	Description
21	Coarse sand over fine sand (CS/FS)
31	Fine gravel over fine sand (FG/FS)
61	Fine anthracite over fine sand (FA/FS)
36	Fine gravel over fine anthracite (FG/FA)
76	Medium anthracite over fine anthracite (MA/FA)

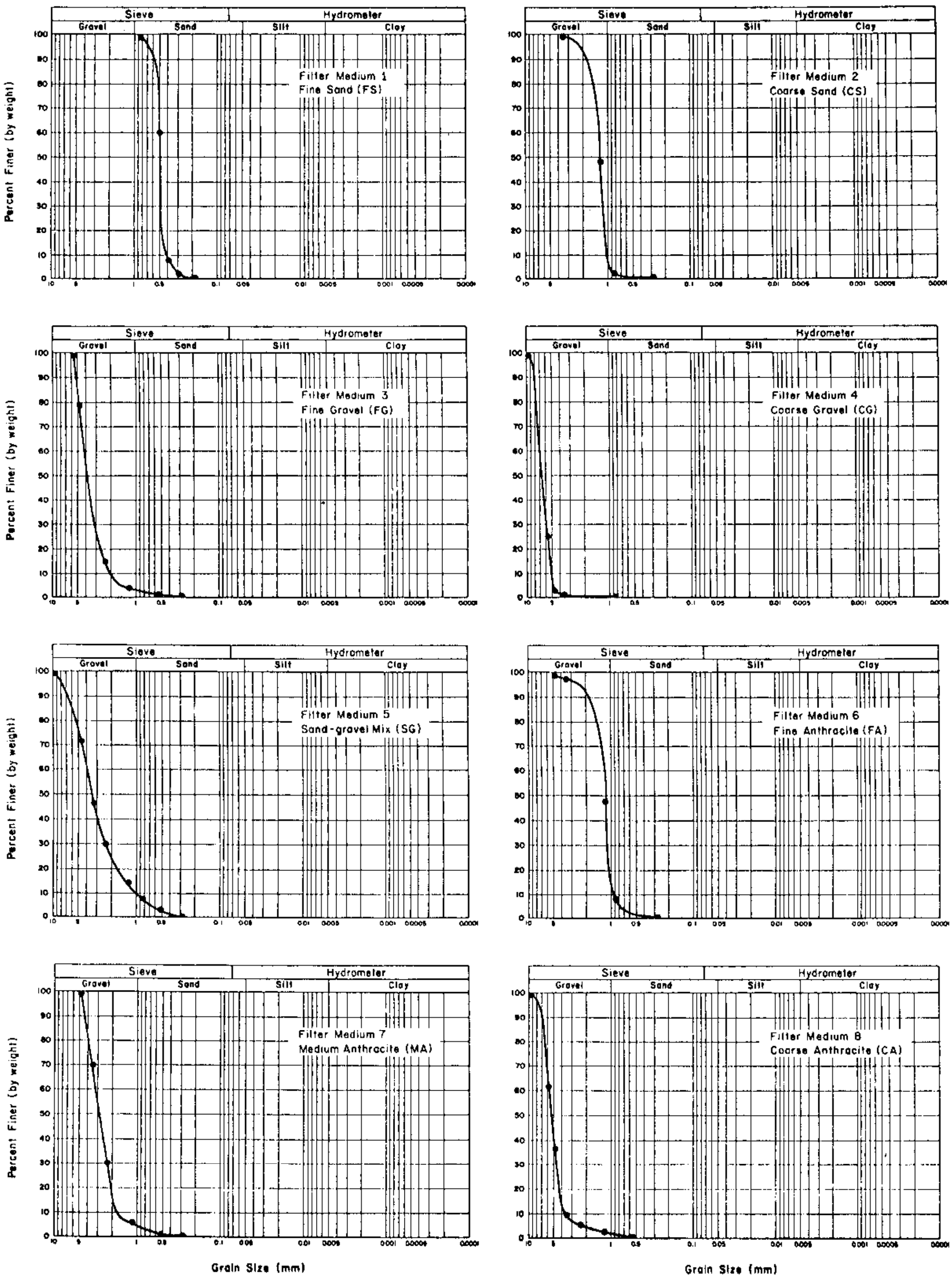

Figure 8. Grain-Size Distributions of Granular Filter Media

according to the following rationale. Since high mass-removal efficiency and a uniform distribution of the deposit within the filter were desired, the best performing single-layer media were used in combinations wherein the grains become finer in the direction of flow.

68. Many fibrous media designed for use in various filtration units are currently produced by a number of manufacturers, and a limited amount of information exists on the performance and capabilities of these media (Burns and Roe, 1971; Wright, Kavanaugh, and Pearson, 1970; Kavanaugh et al., 1971; Calhoun, 1972; and others). However, except for one or two isolated situations (e.g. the Charleston study; Murphy and Zeigler, 1974), field conditions such as those encountered in dredged material disposal areas have not been used to test fibrous media. As summarized in Table 9 the products selected for evaluation in this experimental program were constructed of synthetic, polymeric, or stainless steel fibers; the synthetic fiber media were either woven or nonwoven, which can markedly affect the blinding of a filter material.

69. Water and reagents. Since the dredging of bottom sediments takes place in both fresh and saline water, both of these environments were simulated in the laboratory test program. Ordinary tap water, the ionic composition of which is given in Table 10, was used to model a freshwater environment, and a solution of tap water and some salt additive was used to simulate saline conditions. Although original plans called for the use of synthetic sea salts to represent a saline water environment, these additives were not used for the bulk of the tests because (a) their cost was considered excessive and (b) for purposes of these filtration tests it was not necessary to reproduce a biologically similar medium, but rather to duplicate only the ionic strength of sea water, which required the addition of an inexpensive simple electrolyte-like sodium chloride. In a short series of filtration tests conducted on four different granular filter media with influent composed of solutions of either Ocean ® salts or commercial-grade sodium chloride, the compositions of which are given in Table 10, no difference in performance was observed for either of the two solutions; hence, it was decided that a solution of 30 g/ℓ of a commercial-grade of

Table 9

Characteristics of Fibrous Filter Media

Medium + Identification	Average Pore Size (microns)	Weave Pattern	Basic Material
A (SFR)	-	Random Fiber	Polyester Homofilament
B (SFR)	-	Random Fiber	Polypropylene Homofilament and Nylon Heterofilament
C (SSW)	5	-	Stainless Steel
D (SFW)	-	1-1 Plain	Multifilament
E (SFW)	29	1-1 Plain	Monofilament
F (SFW)	50	2-2 Twill	Monofilament Polypropylene
G (SFW)	-	2-2 Twill	Multifilament Polypropylene

+ Addresses of Manufacturers:

A. Monsanto Company, 800 N. Lindberg Boulevard, St. Louis, Missouri 63166

B. Celanese Corporation, Box 1414, Charlotte, North Carolina 28201

C. Cambridge Wire Cloth Company, Cambridge, Maryland 21613

D. Lamports Company, 2301 Hamilton Avenue, Cleveland, Ohio 44114

E. Tetko, Incorporated, 420 Saw Mill River Road, Elmsford, New York 10523

F. National Filter Media Company, P.O. Box 4217, Hamden, Connecticut 06514

G. National Filter Media Company, P.O. Box 4217, Hamden, Connecticut 06514

Table 10

Ionic Composition of Waters Used for Laboratory Filtration Tests

Constituent	Concentration (mg/ℓ)	
	Ocean R	Tap Water
Cℓ	18400	8.5
Na	10220	5.0
SO_4	2518	24
Mg	1238	11
K	390	1.1
Ca	370	35
HCO_3	142	102
Sr	6.0	0.1
SiO_3	3.0	2.1
PO_4	1.3	0.03
F	1.0	0.1
Li	0.2	0.001
Al	0.04	0.3
Co	0.01	0.003
Fe	0.01	0.08
Cu	0.003	0.03

Note: The salt water used for the laboratory filtration tests had the same ionic composition as tap water with the addition of 18,200 mg/ℓ Cℓ and 11,800 mg/ℓ Na.

granulated sodium chloride ($NaC\ell$) in tap water would satisfactorily simulate a saline water environment.

70. Filtration apparatus. The equipment used for conducting the laboratory tests consisted of (a) large tanks (200 to 400 gallons) for the storage of suspensions, (b) rheostat-controlled pumps, (c) upstream and downstream constant head tanks for overall hydraulic head control, (d) filter columns with sampling ports, and (e) batteries of piezometer tubes. The overall arrangements, as well as some of the structural details, of this equipment are shown in Figures 9, 10, 12, and 13 and some photographs of the test columns for the granular filter media and the test apparatus for the fibrous media are shown in Figures 11 and 14, respectively.

71. Efficiency measurements. Measurements of particle number, turbidity, and suspended mass were used to determine the removal efficiency of the filter media. The number of suspended particles of various sizes was obtained by use of a Model A Coulter counter interfaced with a Nuclear Data multichannel analyzer, and these data were interpreted to yield the suspended particle-size removal efficiency of the filter media. Turbidity readings were taken with a Hach 1860 laboratory turbidimeter and, with the help of gravimetric determinations, were used to evaluate the mass removal efficiency of the filters. Direct gravimetry was employed to determine the mass of suspended solids in the effluents of the filter columns. The method used to correlate turbidity readings and concentrations of suspended solids is presented in Appendix B. For a number of tests on granular filter media, the local mass accumulation was measured at three points along the column, thereby allowing an estimate of the specific deposit and a verification of the mass balance of material collected by the filter.

Operating procedures

72. Standard procedures were used to prepare the artificial suspensions, clean the filter columns, and conduct each test. The variables for all tests are identified in Table 11 for the granular media and in Table 12 for the fibrous media.

73. Selection of variables. In the process of designing each

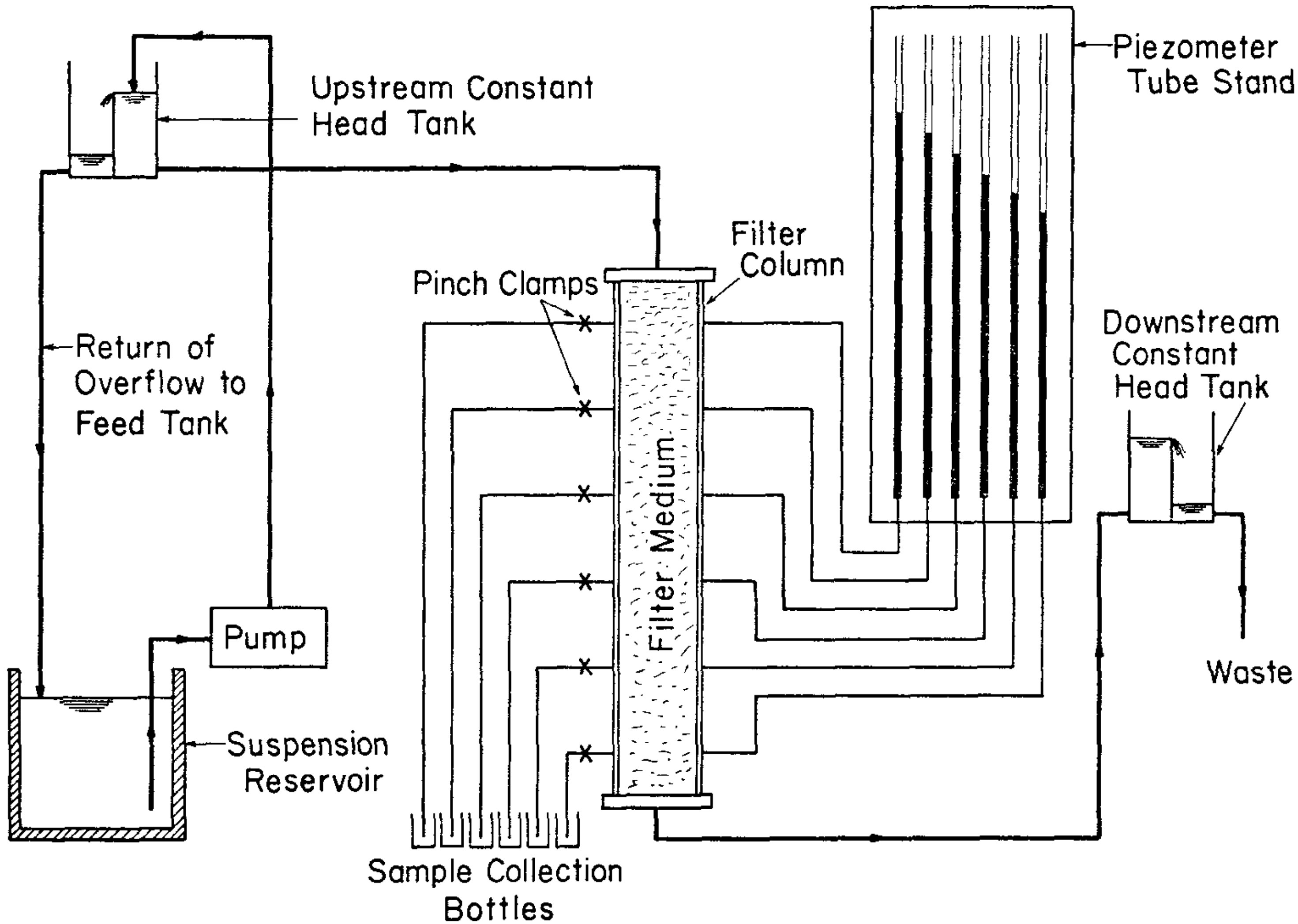

Figure 9. Arrangement of Equipment for Laboratory Testing of Granular Filter Media

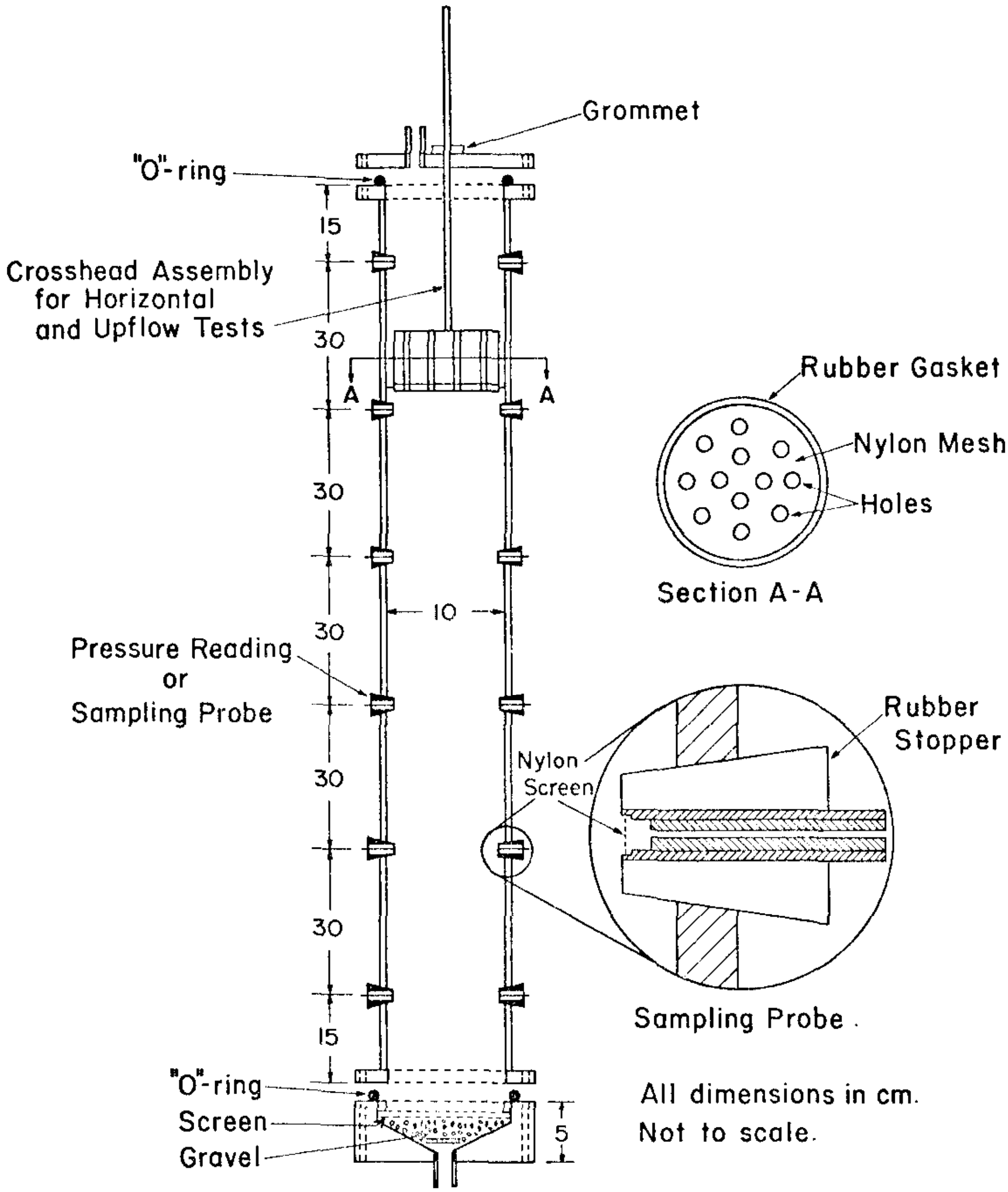

Figure 10. Structural Details of Column for Testing Granular Media

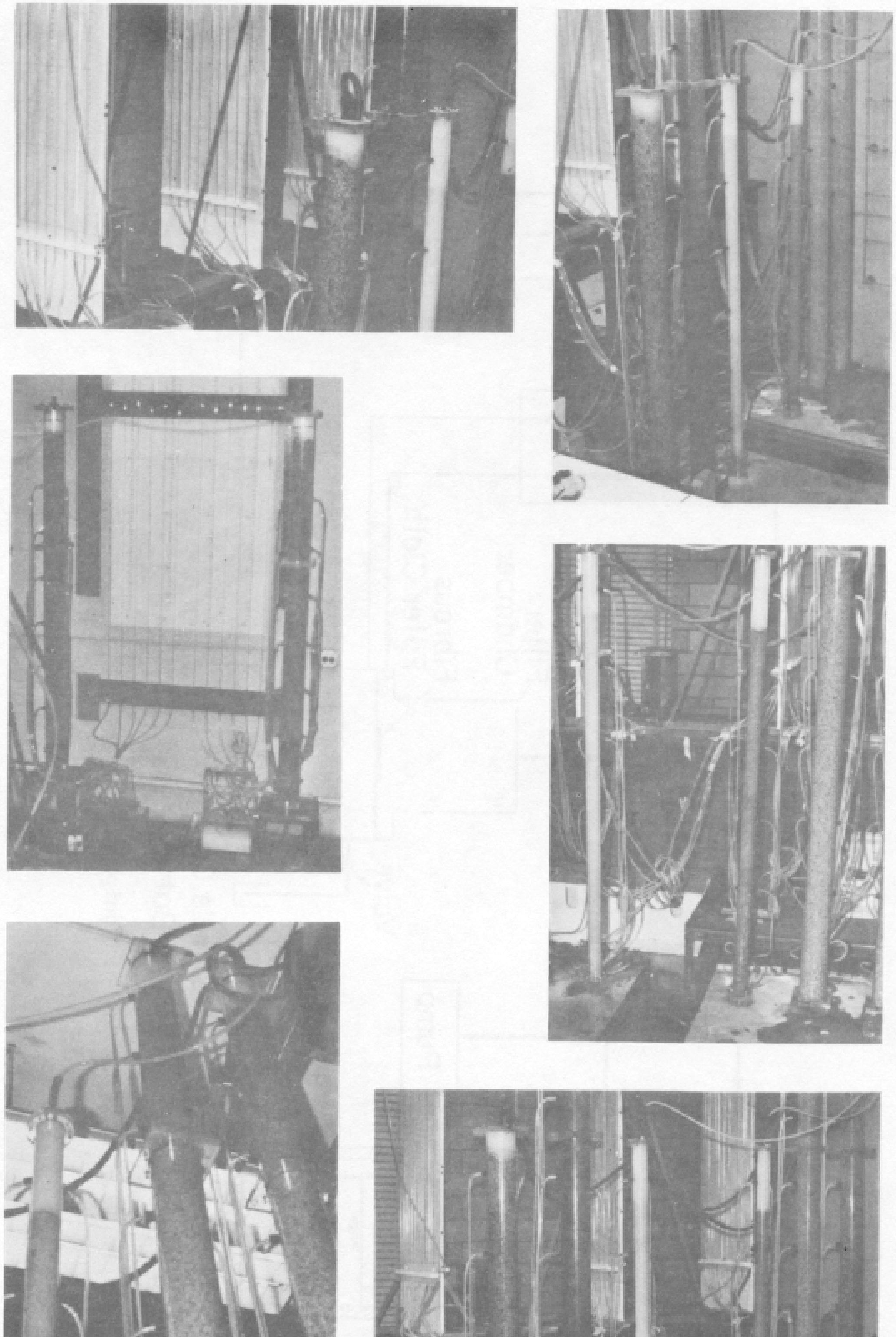

Figure 11. Photographs of Laboratory Tests on Granular Media

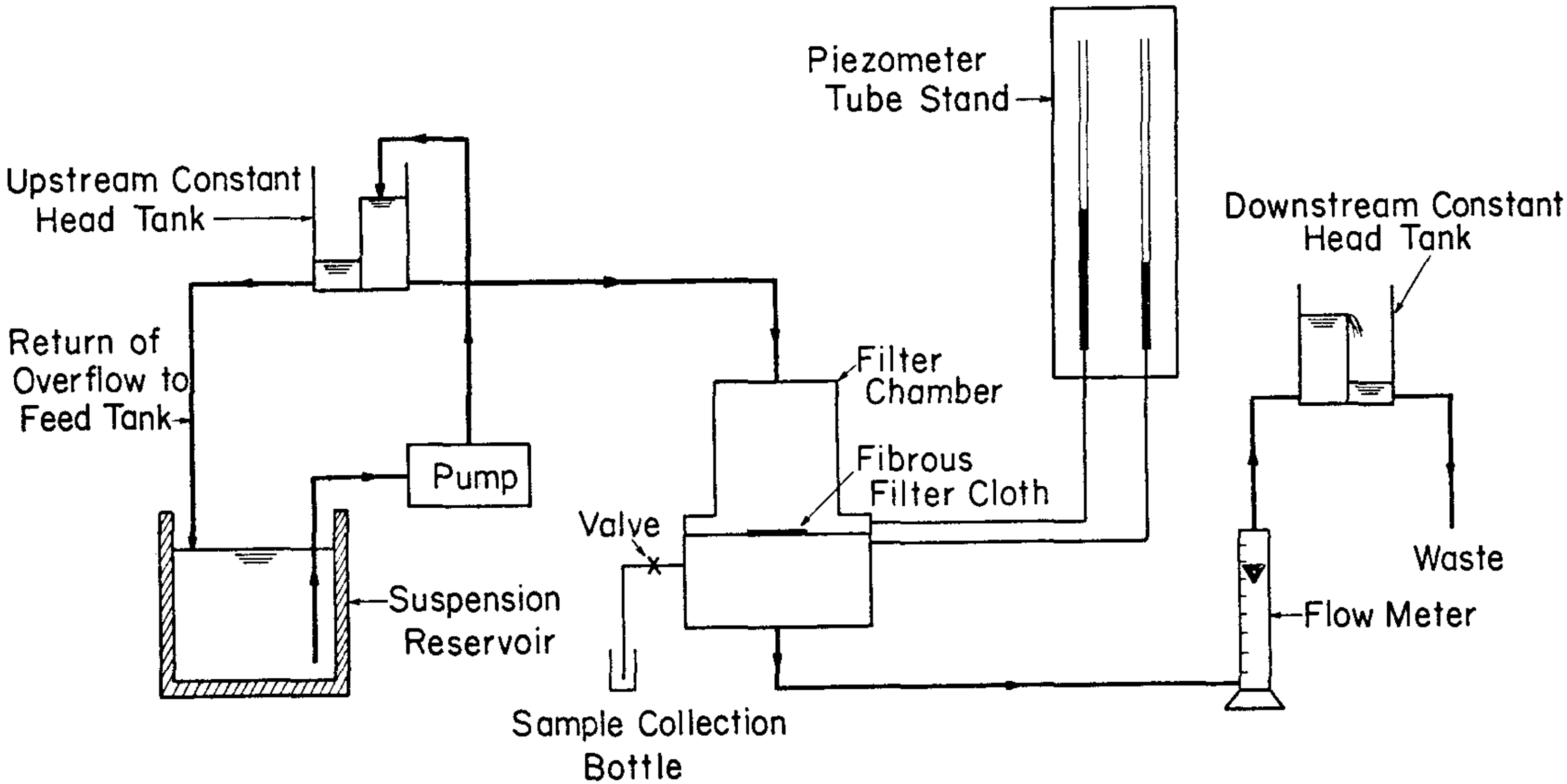

Figure 12. Arrangement of Equipment for Laboratory Testing of Fibrous Filter Media

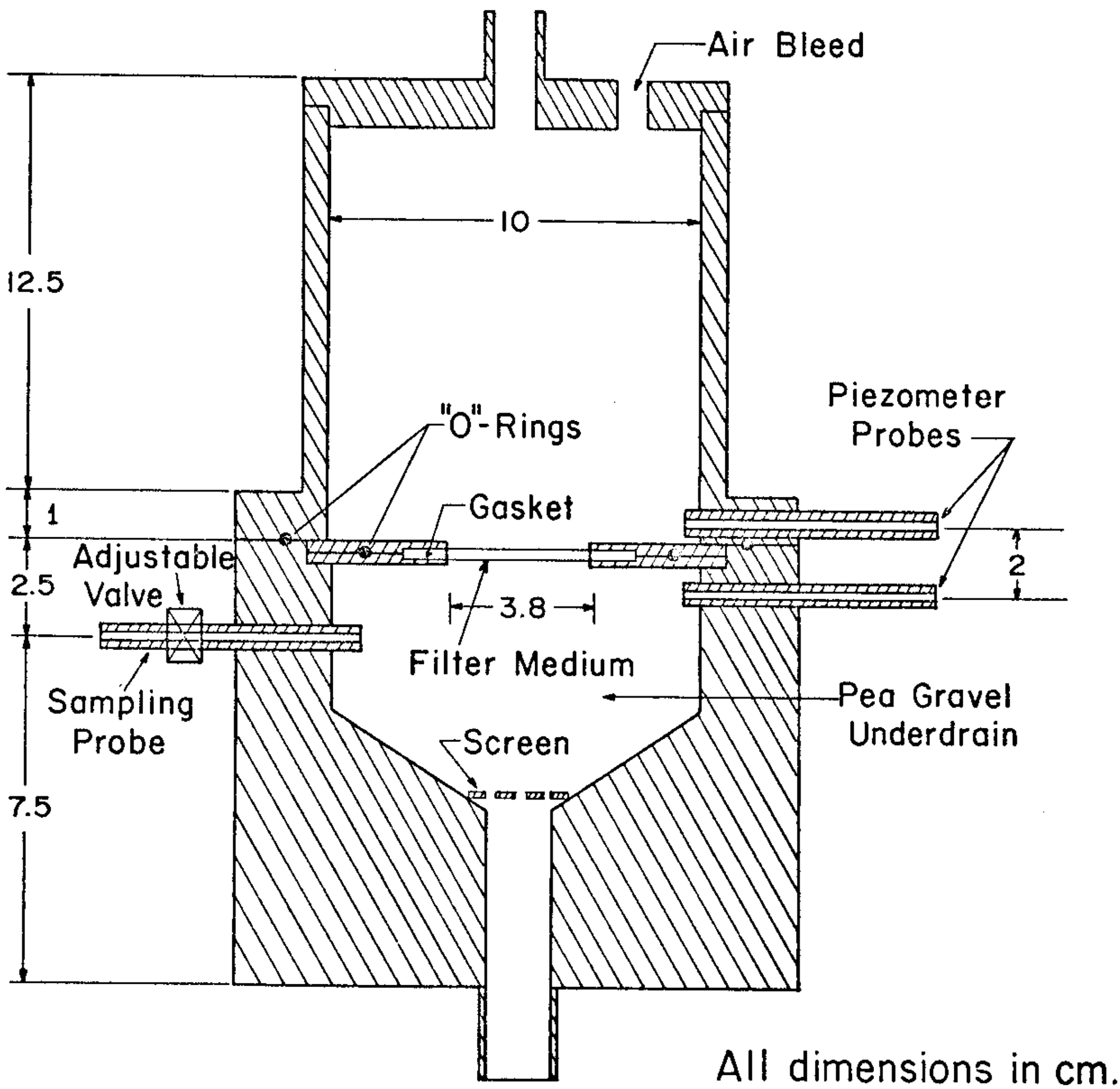

Figure 13. Structural Details of Apparatus for Testing Fibrous Media

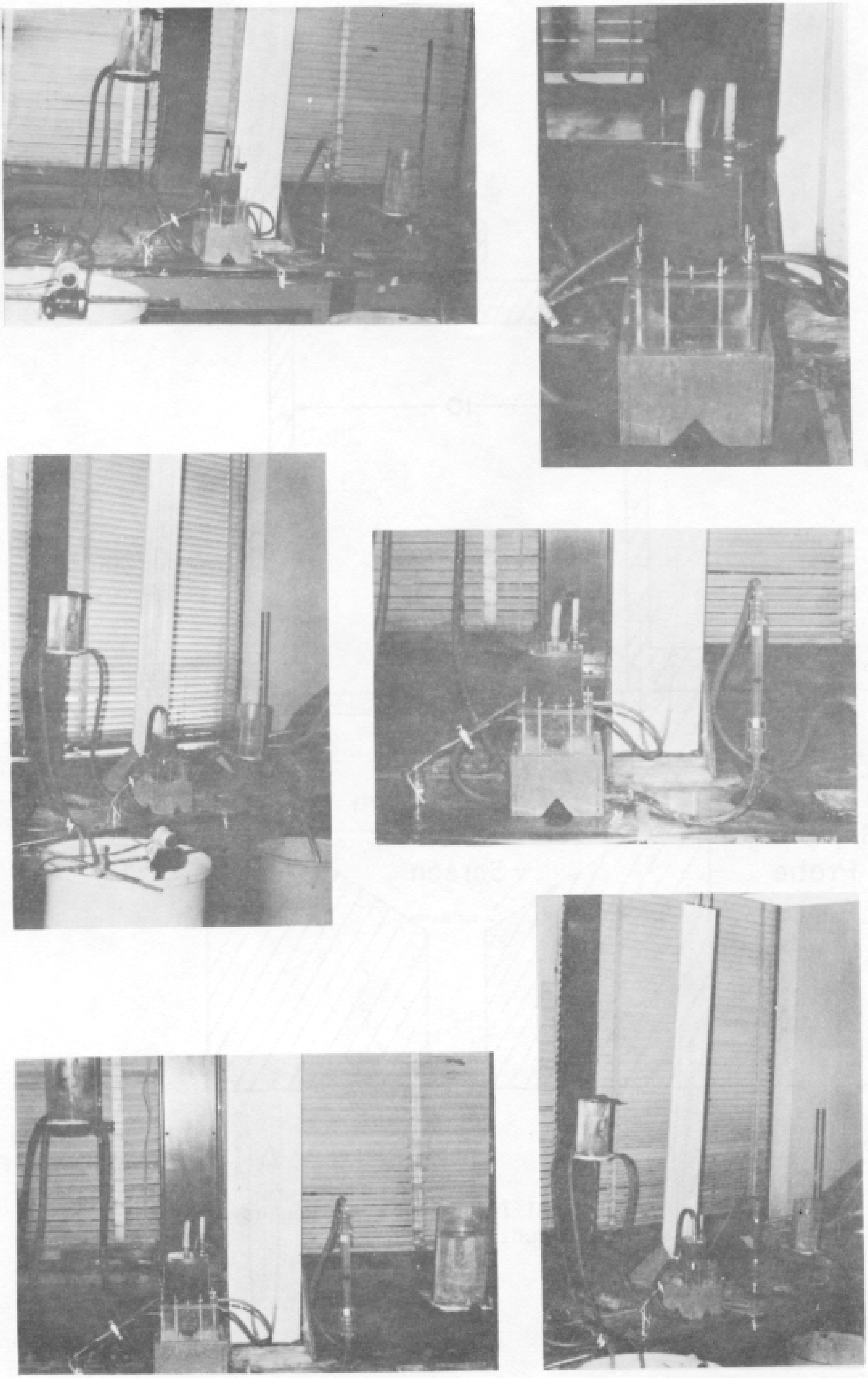

Figure 14. Photographs of Laboratory Tests on Fibrous Media

Table 11

Summary of Laboratory Filtration Tests on Granular Media

Test Number	Filter Medium	Filter Depth (cm)	Type of Suspension	Concentration (mg/ℓ)	Type of Water	Head (cm)	Initial Discharge Velocity (cm/sec)	Direction of Flow
T1V1	FS	152	Kaolinite	100	Fresh	198	0.15	Vertical
T1V2	FS	152	Kaolinite	1,000	Fresh	198	0.16	Vertical
T1V3	FS	152	Grundite	100	Fresh	198	0.13	Vertical
T1V4	FS	152	Grundite	1,000	Fresh	198	0.16	Vertical
T1V8	FS	152	Grundite	1,000	Fresh	107	0.06	Vertical
T1V9	FS	152	Grundite	5,000	Fresh	198	0.13	Vertical
T1V10	FS	152	Grundite	5,000	Fresh	107	0.07	Vertical
T1V11	FS	152	Grundite	10,000	Fresh	198	0.14	Vertical
T1V12	FS	152	Grundite	10,000	Fresh	107	0.07	Vertical
S1V1	FS	152	Kaolinite	100	Salt	198	0.15	Vertical
S1V2	FS	152	Kaolinite	1,000	Salt	198	0.16	Vertical
S1V3	FS	152	Grundite	100	Salt	198	0.14	Vertical
S1V4	FS	152	Grundite	1,000	Salt	198	0.14	Vertical
S1V8	FS	152	Grundite	1,000	Salt	107	0.07	Vertical
S1V11	FS	152	Grundite	10,000	Salt	198	0.13	Vertical
S1V12	FS	152	Grundite	10,000	Salt	107	0.07	Vertical
T1H1	FS	152	Kaolinite	100	Fresh	198	0.13	Horizontal
T1H2	FS	152	Kaolinite	1,000	Fresh	198	0.15	Horizontal
T1H4	FS	152	Grundite	1,000	Fresh	198	0.13	Horizontal
T1H8	FS	152	Grundite	1,000	Fresh	107	0.09	Horizontal
S1H2	FS	152	Kaolinite	1,000	Salt	198	0.16	Horizontal
T2V1	CS	152	Kaolinite	100	Fresh	198	0.62	Vertical
T2V2	CS	152	Kaolinite	1,000	Fresh	198	0.66	Vertical
T2V3	CS	152	Grundite	100	Fresh	198	0.62	Vertical
T2V4	CS	152	Grundite	1,000	Fresh	198	0.62	Vertical
T2V8	CS	152	Grundite	1,000	Fresh	107	0.31	Vertical
T2V9	CS	152	Grundite	5,000	Fresh	198	0.64	Vertical
T2V10	CS	152	Grundite	5,000	Fresh	107	0.49	Vertical
T2V11	CS	152	Grundite	10,000	Fresh	198	0.60	Vertical
T2V12	CS	152	Grundite	10,000	Fresh	107	0.30	Vertical
S2V1	CS	152	Kaolinite	100	Salt	198	0.62	Vertical
S2V2	CS	152	Kaolinite	1,000	Salt	198	0.60	Vertical
S2V3	CS	152	Grundite	100	Salt	198	0.51	Vertical
S2V4	CS	152	Grundite	1,000	Salt	198	0.62	Vertical
S2V8	CS	152	Grundite	1,000	Salt	107	0.33	Vertical
S2V11	CS	152	Grundite	10,000	Salt	198	0.62	Vertical
S2V12	CS	152	Grundite	10,000	Salt	107	0.32	Vertical
T2H1	CS	152	Kaolinite	100	Fresh	198	0.66	Horizontal
T2H2	CS	152	Kaolinite	1,000	Fresh	198	0.62	Horizontal
T2H4	CS	152	Grundite	1,000	Fresh	198	0.66	Horizontal
T2H8	CS	152	Grundite	1,000	Fresh	107	0.33	Horizontal
S2H2	CS	152	Kaolinite	1,000	Salt	198	0.62	Horizontal
T3V5	FG	244	Kaolinite	100	Fresh	45	0.38	Vertical
T3V6	FG	244	Kaolinite	1,000	Fresh	45	0.37	Vertical
T3V7	FG	244	Grundite	100	Fresh	45	0.41	Vertical
T3V8	FG	244	Grundite	1,000	Fresh	45	0.41	Vertical
T3V10	FG	244	Grundite	5,000	Fresh	45	0.39	Vertical
T3V12	FG	244	Grundite	10,000	Fresh	45	0.41	Vertical
S3V5	FG	244	Kaolinite	100	Salt	45	0.35	Vertical
S3V6	FG	244	Kaolinite	1,000	Salt	45	0.35	Vertical
S3V7	FG	244	Grundite	100	Salt	45	0.35	Vertical

(Continued)

Table 11 (Continued)

Test Number	Filter Medium	Filter Depth (cm)	Type of Suspension	Concentration (mg/ℓ)	Type of Water	Head (cm)	Initial Discharge Velocity (cm/sec)	Direction of Flow
S3V8	FG	244	Grundite	1,000	Salt	45	0.36	Vertical
T3H8	FG	244	Grundite	1,000	Fresh	45	0.45	Horizontal
S3H8	FG	244	Grundite	1,000	Salt	45	0.45	Horizontal
T4V5	CG	244	Kaolinite	100	Fresh	45	0.60	Vertical
T4V6	CG	244	Kaolinite	1,000	Fresh	45	0.58	Vertical
T4V7	CG	244	Grundite	100	Fresh	45	0.58	Vertical
T4V8	CG	244	Grundite	1,000	Fresh	45	0.62	Vertical
T4V10	CG	244	Grundite	5,000	Fresh	45	0.60	Vertical
T4V12	CG	244	Grundite	10,000	Fresh	45	0.60	Vertical
S4V8	CG	244	Grundite	1,000	Salt	45	0.60	Vertical
T4H8	CG	244	Grundite	1,000	Fresh	45	0.58	Horizontal
T5V1	SG	244	Kaolinite	100	Fresh	107	0.45	Vertical
T5V2	SG	244	Kaolinite	1,000	Fresh	107	0.35	Vertical
T5V4	SG	244	Grundite	1,000	Fresh	107	0.35	Vertical
T5V5	SG	244	Kaolinite	100	Fresh	45	0.20	Vertical
T5V6	SG	244	Kaolinite	1,000	Fresh	45	0.17	Vertical
T5V7	SG	244	Grundite	100	Fresh	45	0.22	Vertical
T5V8	SG	244	Grundite	1,000	Fresh	45	0.25	Vertical
T5V9	SG	244	Grundite	5,000	Fresh	107	0.43	Vertical
T5V10	SG	244	Grundite	5,000	Fresh	45	0.27	Vertical
T5V11	SG	244	Grundite	10,000	Fresh	107	0.40	Vertical
T5V12	SG	244	Grundite	10,000	Fresh	45	0.23	Vertical
S5V2	SG	244	Kaolinite	1,000	Salt	107	0.39	Vertical
S5V4	SG	244	Grundite	1,000	Salt	107	0.41	Vertical
S5V5	SG	244	Kaolinite	100	Salt	45	0.17	Vertical
S5V6	SG	244	Kaolinite	1,000	Salt	45	0.20	Vertical
S5V8	SG	244	Grundite	1,000	Salt	45	0.19	Vertical
S5V11	SG	244	Grundite	10,000	Salt	107	0.43	Vertical
T5H4	SG	244	Grundite	1,000	Fresh	107	0.51	Horizontal
S5H8	SG	244	Grundite	1,000	Salt	45	0.23	Horizontal
T6V1	FA	152	Kaolinite	100	Fresh	107	0.22	Vertical
T6V2	FA	152	Kaolinite	1,000	Fresh	107	0.24	Vertical
T6V3	FA	152	Grundite	100	Fresh	107	0.25	Vertical
T6V4	FA	152	Grundite	1,000	Fresh	107	0.25	Vertical
T6V5	FA	152	Kaolinite	100	Fresh	45	0.08	Vertical
T6V6	FA	152	Kaolinite	1,000	Fresh	45	0.09	Vertical
T6V7	FA	152	Grundite	100	Fresh	45	0.08	Vertical
T6V8	FA	152	Grundite	1,000	Fresh	45	0.10	Vertical
T6V9	FA	152	Grundite	5,000	Fresh	107	0.20	Vertical
T6V10	FA	152	Grundite	5,000	Fresh	45	0.08	Vertical
T6V11	FA	152	Grundite	10,000	Fresh	107	0.20	Vertical
T6V12	FA	152	Grundite	10,000	Fresh	45	0.08	Vertical
S6V1	FA	152	Kaolinite	100	Salt	107	0.27	Vertical
S6V2	FA	152	Kaolinite	1,000	Salt	107	0.21	Vertical
S6V3	FA	152	Grundite	100	Salt	107	0.24	Vertical
S6V4	FA	152	Grundite	1,000	Salt	107	0.20	Vertical
S6V5	FA	152	Kaolinite	100	Salt	45	0.09	Vertical
S6V6	FA	152	Kaolinite	1,000	Salt	45	0.08	Vertical
S6V7	FA	152	Grundite	100	Salt	45	0.08	Vertical
S6V8	FA	152	Grundite	1,000	Salt	45	0.09	Vertical
S6V11	FA	152	Grundite	10,000	Salt	107	0.22	Vertical

(Continued)

Table 11 (Continued)

Test Number	Filter Medium	Filter Depth (cm)	Type of Suspension	Concentration (mg/ℓ)	Type of Water	Head (cm)	Initial Discharge Velocity (cm/sec)	Direction of Flow
T6H1	FA	152	Kaolinite	100	Fresh	107	0.26	Horizontal
T6H2	FA	152	Kaolinite	1,000	Fresh	107	0.31	Horizontal
T6H6	FA	152	Kaolinite	1,000	Fresh	45	0.09	Horizontal
S6H4	FA	152	Grundite	1,000	Salt	107	0.25	Horizontal
T7V1	MA	152	Kaolinite	100	Fresh	107	0.58	Vertical
T7V2	MA	152	Kaolinite	1,000	Fresh	107	0.62	Vertical
T7V3	MA	152	Grundite	100	Fresh	107	0.58	Vertical
T7V4	MA	152	Grundite	1,000	Fresh	107	0.59	Vertical
T7V5	MA	152	Kaolinite	100	Fresh	45	0.21	Vertical
T7V6	MA	152	Kaolinite	1,000	Fresh	45	0.20	Vertical
T7V7	MA	152	Grundite	100	Fresh	45	0.20	Vertical
T7V8	MA	152	Grundite	1,000	Fresh	45	0.26	Vertical
T7V9	MA	152	Grundite	5,000	Fresh	107	0.54	Vertical
T7V10	MA	152	Grundite	5,000	Fresh	45	0.28	Vertical
T7V11	MA	152	Grundite	10,000	Fresh	107	0.52	Vertical
T7V12	MA	152	Grundite	10,000	Fresh	45	0.28	Vertical
S7V1	MA	152	Kaolinite	100	Salt	107	0.57	Vertical
S7V2	MA	152	Kaolinite	1,000	Salt	107	0.54	Vertical
S7V3	MA	152	Grundite	100	Salt	107	0.59	Vertical
S7V4	MA	152	Grundite	1,000	Salt	107	0.54	Vertical
S7V5	MA	152	Kaolinite	100	Salt	45	0.25	Vertical
S7V6	MA	152	Kaolinite	1,000	Salt	45	0.26	Vertical
S7V7	MA	152	Grundite	100	Salt	45	0.26	Vertical
S7V8	MA	152	Grundite	1,000	Salt	45	0.26	Vertical
T7H1	MA	152	Kaolinite	100	Fresh	107	0.65	Horizontal
T7H2	MA	152	Kaolinite	1,000	Fresh	107	0.54	Horizontal
T7H6	MA	152	Kaolinite	1,000	Fresh	45	0.27	Horizontal
S7H4	MA	152	Grundite	1,000	Salt	107	0.52	Horizontal
T8V5	CA	152	Kaolinite	100	Fresh	45	0.63	Vertical
T8V6	CA	152	Kaolinite	1,000	Fresh	45	0.62	Vertical
T8V7	CA	152	Grundite	100	Fresh	45	0.62	Vertical
T8V8	CA	152	Grundite	1,000	Fresh	45	0.56	Vertical
T8V10	CA	152	Grundite	5,000	Fresh	45	0.56	Vertical
T8V12	CA	152	Grundite	10,000	Fresh	45	0.60	Vertical
S8V5	CA	152	Kaolinite	100	Salt	45	0.58	Vertical
S8V6	CA	152	Kaolinite	1,000	Salt	45	0.58	Vertical
S8V7	CA	152	Grundite	100	Salt	45	0.64	Vertical
S8V8	CA	152	Grundite	1,000	Salt	45	0.59	Vertical
T8H8	CA	152	Grundite	1,000	Fresh	45	0.62	Horizontal
T21V1	CS/FS	91 + 61	Kaolinite	100	Fresh	198	0.21	Vertical
T21V2	CS/FS	91 + 61	Kaolinite	1,000	Fresh	198	0.21	Vertical
T21V3	CS/FS	91 + 61	Grundite	100	Fresh	198	0.15	Vertical
T21V4	CS/FS	91 + 61	Grundite	1,000	Fresh	198	0.21	Vertical
T21V8	CS/FS	91 + 61	Grundite	1,000	Fresh	107	0.12	Vertical
T21V9	CS/FS	91 + 61	Grundite	5,000	Fresh	198	0.25	Vertical
T21V10	CS/FS	91 + 61	Grundite	5,000	Fresh	107	0.12	Vertical
T21V11	CS/FS	91 + 61	Grundite	10,000	Fresh	198	0.21	Vertical
T21V12	CS/FS	91 + 61	Grundite	10,000	Fresh	107	0.12	Vertical
S21V1	CS/FS	91 + 61	Kaolinite	100	Salt	198	0.18	Vertical
S21V2	CS/FS	91 + 61	Kaolinite	1,000	Salt	198	0.21	Vertical
S21V3	CS/FS	91 + 61	Grundite	100	Salt	198	0.18	Vertical

(Continued)

Table 11 (Concluded)

Test Number	Filter Medium	Filter Depth (cm)	Type of Suspension	Concentration (mg/ℓ)	Type of Water	Head (cm)	Initial Discharge Velocity (cm/sec)	Direction of Flow
S21V8	CS/FS	91 + 61	Grundite	1,000	Salt	107	0.12	Vertical
S21V11	CS/FS	91 + 61	Grundite	10,000	Salt	198	0.19	Vertical
T31V1	FG/FS	91 + 61	Kaolinite	100	Fresh	107	0.20	Vertical
T31V2	FG/FS	91 + 61	Kaolinite	1,000	Fresh	107	0.18	Vertical
T31V3	FG/FS	91 + 61	Grundite	100	Fresh	107	0.25	Vertical
T31V4	FG/FS	91 + 61	Grundite	1,000	Fresh	107	0.17	Vertical
T31V8	FG/FS	91 + 61	Grundite	1,000	Fresh	45	0.06	Vertical
T31V9	FG/FS	91 + 61	Grundite	5,000	Fresh	107	0.18	Vertical
T31V10	FG/FS	91 + 61	Grundite	5,000	Fresh	45	0.06	Vertical
T31V11	FG/FS	91 + 61	Grundite	10,000	Fresh	107	0.23	Vertical
T31V12	FG/FS	91 + 61	Grundite	10,000	Fresh	45	0.08	Vertical
S31V1	FG/FS	91 + 61	Kaolinite	100	Salt	107	0.21	Vertical
S31V2	FG/FS	91 + 61	Kaolinite	1,000	Salt	107	0.21	Vertical
S31V3	FG/FS	91 + 61	Grundite	100	Salt	107	0.21	Vertical
S31V4	FG/FS	91 + 61	Grundite	1,000	Salt	107	0.21	Vertical
S31V7	FG/FS	91 + 61	Grundite	100	Salt	45	0.08	Vertical
T61V4	FA/FS	91 + 61	Grundite	1,000	Fresh	107	0.10	Vertical
T61V8	FA/FS	91 + 61	Grundite	1,000	Fresh	45	0.04	Vertical
T61V9	FA/FS	91 + 61	Grundite	5,000	Fresh	107	0.12	Vertical
T61V10	FA/FS	91 + 61	Grundite	5,000	Fresh	45	0.04	Vertical
T61V11	FA/FS	91 + 61	Grundite	10,000	Fresh	107	0.15	Vertical
T61V12	FA/FS	91 + 61	Grundite	10,000	Fresh	45	0.05	Vertical
S61V7	FA/FS	91 + 61	Grundite	100	Salt	45	0.04	Vertical
S61V8	FA/FS	91 + 61	Grundite	1,000	Salt	45	0.05	Vertical
S61V11	FA/FS	91 + 61	Grundite	10,000	Salt	107	0.11	Vertical
T36V4	FG/FA	91 + 61	Grundite	1,000	Fresh	107	0.40	Vertical
T36V8	FG/FA	91 + 61	Grundite	1,000	Fresh	45	0.11	Vertical
T36V9	FG/FA	91 + 61	Grundite	5,000	Fresh	107	0.26	Vertical
T36V10	FG/FA	91 + 61	Grundite	5,000	Fresh	45	0.13	Vertical
T36V11	FG/FA	91 + 61	Grundite	10,000	Fresh	107	0.41	Vertical
T36V12	FG/FA	91 + 61	Grundite	10,000	Fresh	45	0.14	Vertical
S36V1	FG/FA	91 + 61	Kaolinite	100	Salt	107	0.35	Vertical
S36V2	FG/FA	91 + 61	Kaolinite	1,000	Salt	107	0.35	Vertical
S36V3	FG/FA	91 + 61	Grundite	100	Salt	107	0.35	Vertical
S36V4	FG/FA	91 + 61	Grundite	1,000	Salt	107	0.43	Vertical
S36V7	FG/FA	91 + 61	Grundite	100	Salt	45	0.15	Vertical
T76V1	MA/FA	91 + 61	Kaolinite	100	Fresh	107	0.25	Vertical
T76V2	MA/FA	91 + 61	Kaolinite	1,000	Fresh	107	0.29	Vertical
T76V4	MA/FA	91 + 61	Grundite	1,000	Fresh	107	0.20	Vertical
T76V5	MA/FA	91 + 61	Kaolinite	100	Fresh	45	0.10	Vertical
T76V6	MA/FA	91 + 61	Kaolinite	1,000	Fresh	45	0.12	Vertical
T76V7	MA/FA	91 + 61	Grundite	100	Fresh	45	0.08	Vertical
T76V8	MA/FA	91 + 61	Grundite	1,000	Fresh	45	0.10	Vertical
T76V9	MA/FA	91 + 61	Grundite	5,000	Fresh	107	0.23	Vertical
T76V10	MA/FA	91 + 61	Grundite	5,000	Fresh	45	0.24	Vertical
T76V11	MA/FA	91 + 61	Grundite	10,000	Fresh	107	0.21	Vertical
T76V12	MA/FA	91 + 61	Grundite	10,000	Fresh	45	0.15	Vertical
S76V5	MA/FA	91 + 61	Kaolinite	100	Salt	45	0.10	Vertical
S76V6	MA/FA	91 + 61	Kaolinite	1,000	Salt	45	0.11	Vertical
S76V7	MA/FA	91 + 61	Grundite	100	Salt	45	0.11	Vertical
S76V8	MA/FA	91 + 61	Grundite	1,000	Salt	45	0.12	Vertical

Table 12

Summary of Laboratory Filtration Tests on Fibrous Media

Filter Medium Identification	Type of Filter Medium	Type of Suspended Solids	Fresh Water: Concentration of Suspended Solids (g/ℓ)		Salt Water: Concentration of Suspended Solids (g/ℓ)	
			1	10	1	10
A	SFR	Kaolinite	X	X	X	X
		Grundite	X	XX	X	X
B	SFR	Kaolinite	X	X	X	X
		Grundite	X	XX	X	X
C	SSW	Kaolinite	X	X	–	X
		Grundite	X	–	X	X
D	SFW	Kaolinite	X	X	–	X
		Grundite	X	XX	–	X
E	SFW	Kaolinite	X	X	–	X
		Grundite	X	XX	–	X
F	SFW	Kaolinite	–	X	–	X
		Grundite	X	XX	–	X
G	SFW	Kaolinite	X	–	–	X
		Grundite	–	XX	–	X

Notes:

1. The symbol X indicates that a test was conducted at an initial flow velocity of approximately 1.4 cm/sec.
2. The symbol XX indicates that a second test was conducted with an initial flow velocity much larger than the usual 1.4 cm/sec.
3. Dashes indicate that no tests were conducted.

laboratory test, the filter medium was selected first; then, the remaining dominant variables were chosen as follows:

- a. Type of water. Depending on the type of environment to be simulated, fresh or salt water was selected.
- b. Type of suspension. Kaolinite or Grundite was used to obtain the desired grain-size distribution for the suspended solids.
- c. Concentration. The concentration of suspended solids was chosen to lie between 0.1 and 10 g/ℓ.
- d. Filter depth. Single-layer granular media were placed in columns to a depth of either 5 or 8 ft; dual-layer granular media always had a total depth of 5 ft with the first medium in the direction of flow being 3 ft deep. Virtually all tests on fibrous media were performed with single layers only.
- e. Flow rate. All laboratory tests were conducted under constant overall hydraulic head, rather than constant flow rate; this situation probably affords a more realistic simulation of field operating conditions where expensive flow-rate control equipment are not used and where, due to clogging, flow rates tend to decline while hydraulic heads are maintained approximately constant. However, the initial flow rates did vary, and they were dictated by the head selected. For granular media one low and one high initial flow rate were used, but for fibrous media the initial flow rate was always about 1.4 cm/sec (relatively high).
- f. Flow direction. The bulk of the granular media tests were conducted in a vertical downflow mode, but a limited number of tests were performed to evaluate the advantages or disadvantages in filter performance obtained with horizontal flow or upflow. The flow direction for the fibrous media was always vertically downward and perpendicular to the face of the filter.

74. Preparation of suspensions. The suspensions were prepared by first dispersing small portions of solids in water by use of high-speed electrical mixers (Waring or Hamilton Beach blenders) and then adding these mixtures to the water in the storage tank. Mechanical stirrers fastened on the tank wall continuously mixed the suspension during each test. For the tests involving salt water, an equilibration period of several hours was allowed between the time when the salt was added and the time when the suspended solids were added to the water.

Before starting each test, the suspension was continuously agitated in the tank for at least thirty minutes. During the time of each test (usually eight hours), the electrophoretic mobility of the suspended particles and the pH of the suspension did not change.

75. Preparation of filter columns. After each test sequence was finished, the filter columns were emptied and thoroughly cleaned with tap water. Influent and effluent lines, upstream and downstream constant head tanks, and other parts of the test assembly were cleaned periodically. The granular filter media were placed in the columns in about 6-inch layers and compacted by striking the sides of the column. The resulting void ratios ranged from 0.50 to 0.55 for the sands and gravels (with the exception of the coarse gravel, which had an average void ratio of 0.65) and from 0.75 to 0.80 for the anthracites. After the filter material was placed to a predetermined depth, it was washed in the direction of flow (without fluidization) with tap water in order to remove any existing dust or fine particles that might alter the nature of the filtrate samples.

76. Conduct of test. A typical test involved the following operations:

a. Initiation of test. After the equipment was prepared and inspected, the filter suspension was pumped into the upstream constant head tank and allowed to flow by gravity through the column to the downstream constant head tank. No attempt was made to eliminate the trapped air, which effectively decreased the void volume of the filter medium.

b. Sampling. Samples of the influent, effluent, and intermediate filtrate were taken approximately 0.5, 1, 2, 4, and 8 hours after the tests began; in the case of the fibrous filter media, samples were taken more frequently during the first hour of operation.

c. Discharge and head loss readings. The discharge of each column and the water levels in the piezometer tubes were measured whenever filtrate samples were collected.

d. Termination of test. Each test was terminated either after eight hours of operation or when the flow rate decreased by about one order of magnitude from the initial flow rate.

Supplementary studies and tests

77. A limited number of supplementary tests were conducted to examine additional filter configurations or operating procedures and to obtain added insight into the influence of particle characteristics on filter performance. As summarized in Table 13, filtration tests were performed to evaluate the effects of upflow conditions, suspended organics, and intermittent operation, as well as to assess the efficiency of backwashing. Table 14 describes various series of tests employing saw dust, straw, wood chips, or wood shavings as filter media; in addition, a brief study of vacuum dewatering was undertaken, and the results that were obtained are summarized in Appendix C.

78. For the needs of this research study, particular correlations were developed between turbidity and mass concentration for the Grundite and kaolinite suspensions according to the method described in Appendix B. Since varying periods of time may be required for the properties of clays to equilibrate with their aquatic environment, a series of tests were made to measure the pH and electrophoretic mobility of the Grundite and kaolinite suspensions as a function of time. Neither mobility nor pH showed much variation in a typical 8 hour test. The mobilities were generally small (1.5 and 1.9 μ/sec/volt/cm for kaolinite and Grundite suspensions, respectively) in tap water, and approached zero in simulated sea water.

Field Filtration Tests

79. Two series of field filtration tests were conducted to evaluate and compare the field performance of several granular filter media that were tested in the laboratory. Since the composition and concentration of the disposal area supernatants were dictated in large part by the operating conditions that prevailed at the time of testing, the field suspensions were different from those used in the laboratory tests. Specifically, except for a limited number of tests in which organic sludge particles were added to the clay, the laboratory suspensions consisted only of nonvolatile suspended solids, and the amount

Table 13

Summary of Supplementary Tests on Granular Filter Media

Test Number	Filter Medium	Concentration (mg/ℓ)	Head (cm)	Initial Discharge Velocity (cm/sec)	Direction of Flow
T1V13*	FS	5,000	107	0.07	Downflow
T2V13*	CS	5,000	107	0.30	Downflow
T6V13*	FA	5,000	45	0.09	Downflow
T7V13*	MA	5,000	45	0.21	Downflow
T1V14	FS	10,000	107	0.05	Upflow
T2V14	CS	10,000	107	0.22	Upflow
T6V14	FA	10,000	45	0.07	Upflow
T7V14	MA	10,000	45	0.18	Upflow
T1V15**	FS	5,000	198	0.07	Downflow
T2V15**	CS	5,000	198	0.28	Downflow
T6V15**	FA	5,000	107	0.09	Downflow
T7V15**	MA	5,000	107	0.20	Downflow

Notes:

For all tests the filter depth was 152 cm and the suspension was Grundite in fresh water.

* 2000 mg/ℓ digested sludge was added to the influent.

** After an initial run of 7 hours, there was a 44 hour rest period; a second run was then conducted for 8 hours or until clogging.

Table 14

Summary of Laboratory Filtration Tests on Nonconventional Filter Media

Material	Direction of Flow	Initial Discharge Velocity (cm/sec)	Remarks
Hay	Downflow	0.04	Channelized flow occurred
	Upflow	0.03	
Sawdust	Downflow	-	Very low permeability; column clogged fast by blinding of upstream face of filter
	Upflow	-	
Wood Chips	Downflow	0.10	Channelized flow occurred
	Upflow	0.10	
Wood Shavings	Downflow	-	Columns clogged quickly
	Upflow	-	

Notes:

Type of water : Fresh

Suspension : Grundite

Concentration : 10,000 mg/ℓ

Filter Depth : 152 cm

Head : 107 cm

of suspended solids in the laboratory suspensions was essentially constant for any given series of tests.

Test sites

80. Two different field test sites were selected primarily on the basis of the water environment in which the dredging took place. The saltwater site was located at the Military Ocean Terminal-Sunny Point (MOTSU) near Wilmington, North Carolina, and the freshwater site was the Penn 7 disposal area near Toledo, Ohio. The tests at MOTSU were conducted in late January 1975 and the tests at Penn 7 were performed during the third week of April 1975.

Equipment

81. The equipment used for these field tests was essentially the same as that employed for the laboratory tests. However, instead of downstream constant head tanks, the elevations of the filter column discharge tubes were adjusted to yield initial flow rates similar to those used for the laboratory tests. The arrangements of the equipment at each site are shown in the schematic diagrams and photographs presented in Figures 15 through 18.

Variables and parameters

82. All of the single-and dual-layer granular filter media that were used in the laboratory tests were tested during both series of field tests. The characteristics and grain-size distributions of these media have been given in Tables 7 and 8 and in Figure 8. The direction of flow was always vertical (downflow), and the filter depth for single layer tests was always 5 ft. For tests on dual-layer media, the top and bottom layers had depths of 3 and 2 ft, respectively. Tests with two different initial flow rates were conducted for each filter medium; the initial flow rates were controlled by establishing an overall hydraulic head difference, which was then maintained constant throughout the duration of each test (this same procedure was followed in the laboratory tests). As mentioned previously, the composition and concentration of the field filter suspensions were dictated by the conditions that existed within the containment areas at the time of testing, but the time-dependent properties of the influent and effluent suspensions

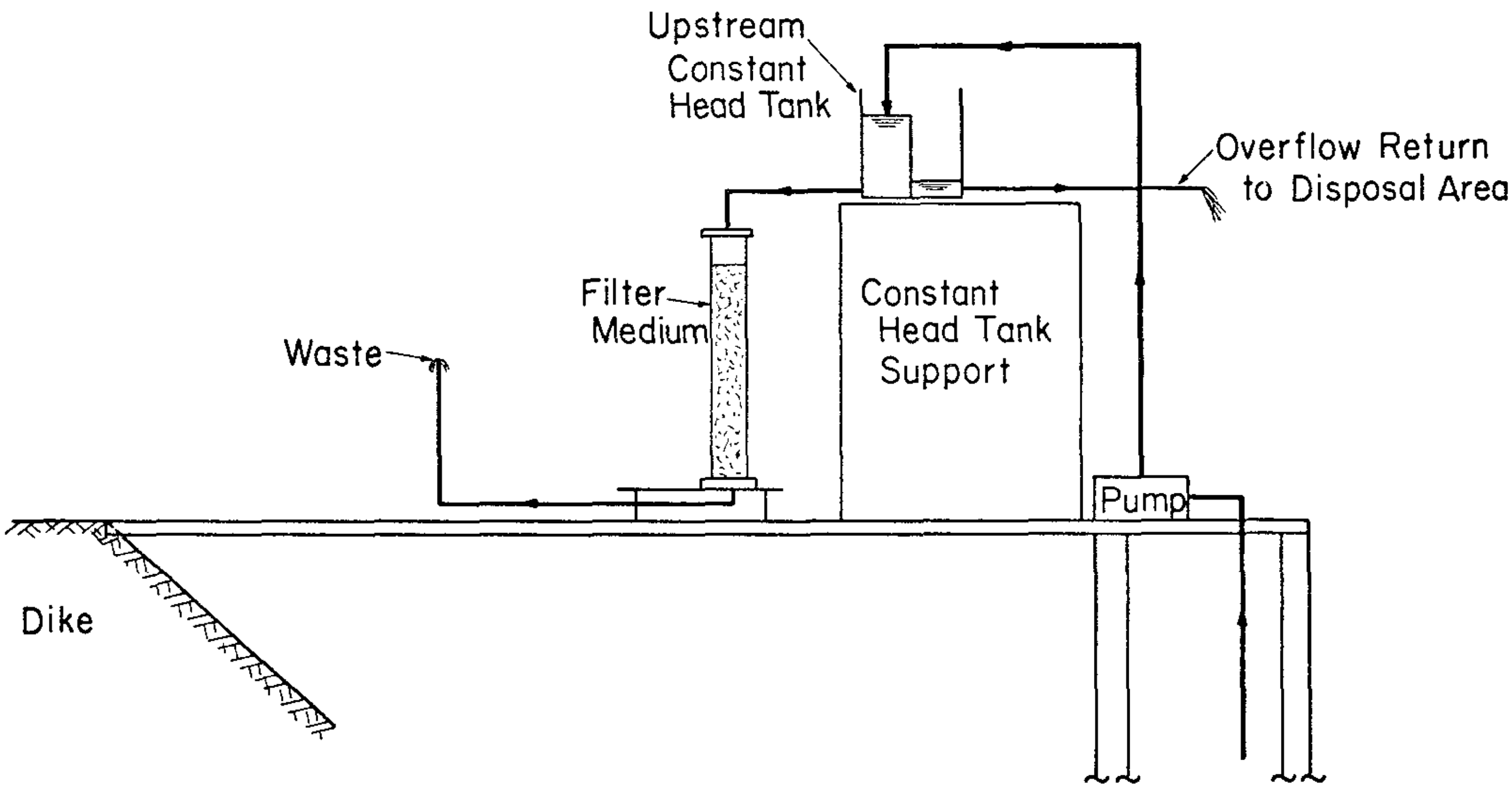

Figure 15. Arrangement of Equipment for Field Filtration Tests at MOTSU

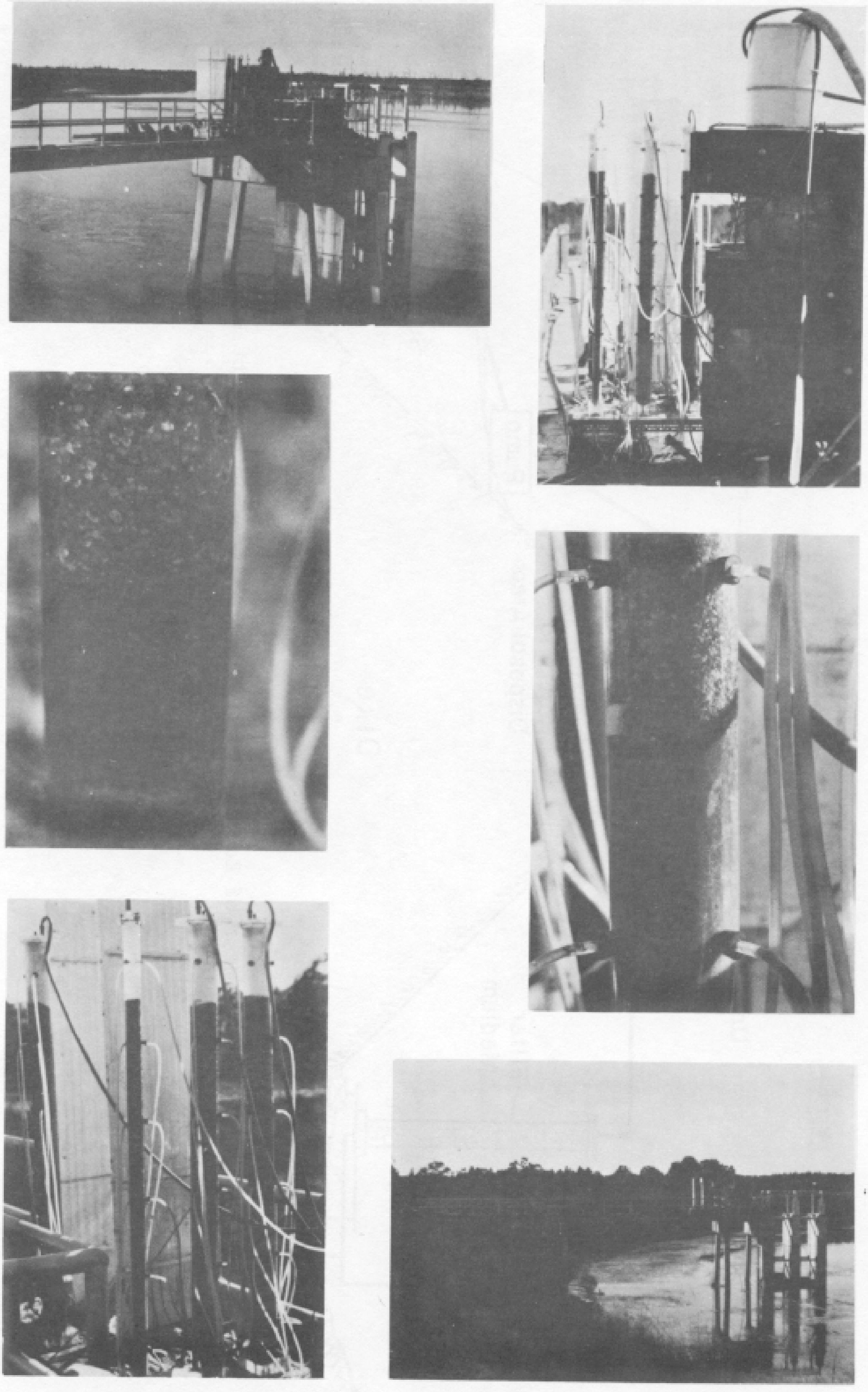

Figure 16. Photographs of Field Tests at MOTSU

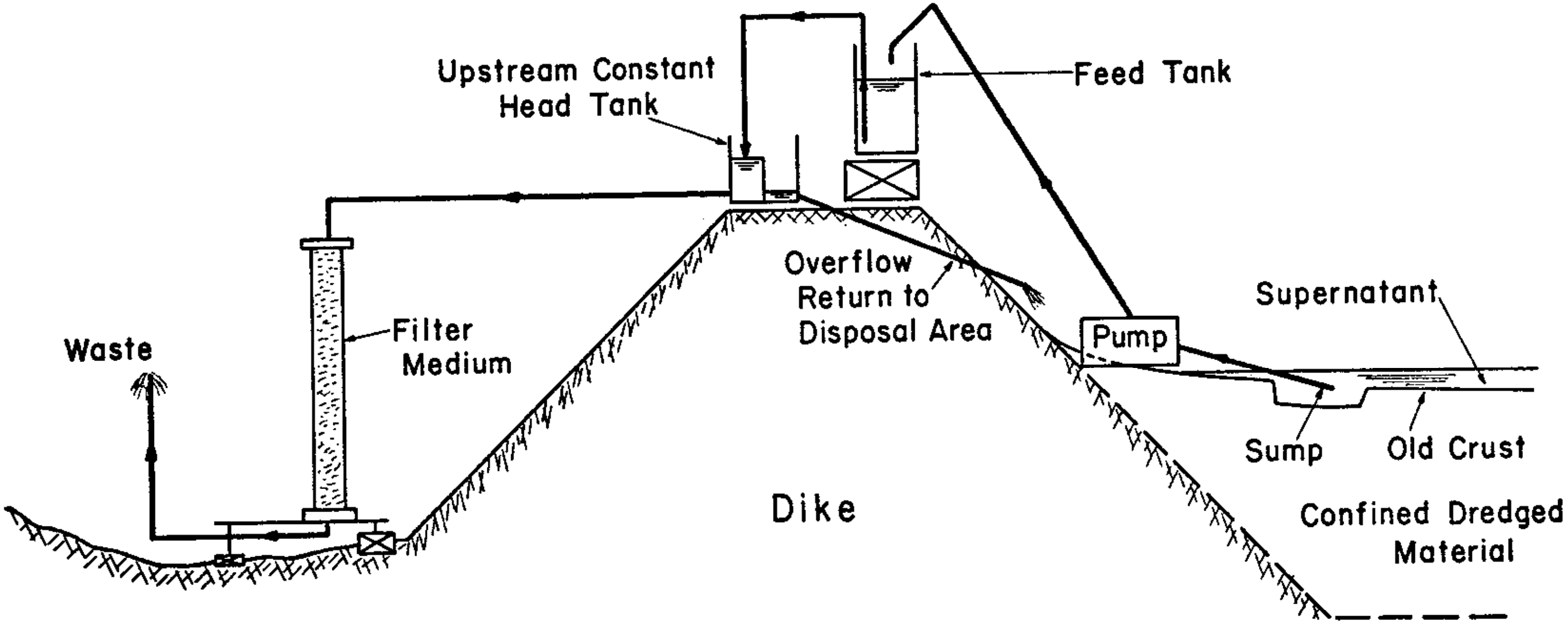

Figure 17. Arrangement of Equipment for Field Filtration Tests at Penn 7

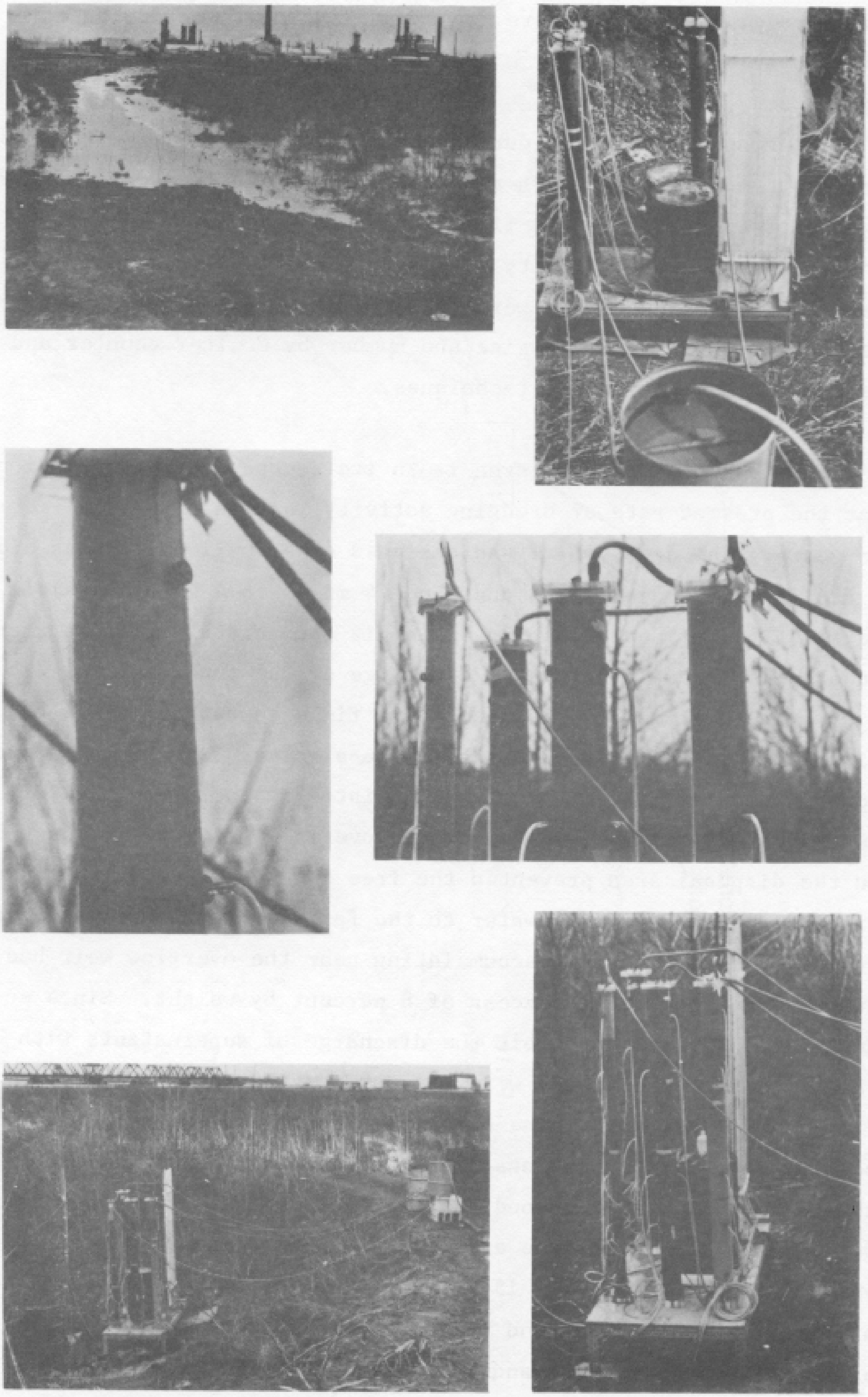

Figure 18. Photographs of Field Tests at Penn 7

passing through the filters were monitored several times during each test.

Data collected

83. At specified times during each test, the rate of discharge was measured for each filter column and filtrate samples were collected from points along each column. The filtrate and supernatant samples were tested immediately for turbidity with a Hach model DR-EL field turbidimeter, and selected samples were transported to the laboratory for the determination of particle size and number by Coulter counter and solids content by gravimetric techniques.

MOTSU

84. The MOTSU disposal area is in its second year of operation and, at the present rate of dredging activity, has an expected lifetime of ten years. The dike, which was designed as a small dam, is as high as 40 ft (13 meters) in places and about 4 miles (6.4 kilometers) in perimeter. The effluent sluicing device is a concrete structure with wooden stop-logs that control the discharge of the supernatants.

85. At the time during which these field tests took place, an undesirable situation existed at the disposal area. Due to an unfortunate combination of circumstances that existed at the site (the inflow pipe was located relatively close to the overflow weir; the topography within the disposal area prevented the free flow of water to the weir; and wind tended to carry the water to the farside of the disposal area), the so-called "supernatants" accumulating near the overflow weir had a suspended solids content in excess of 8 percent by weight. Since environmental constraints prohibit the discharge of supernatants with such high solids content, the weir was not functioning.

86. An inspection of the disposal site showed that (a) water was ponding at various locations within the containment facility; (b) the ponded water was of good quality (turbidity on the order of 50 to 100 JTU); (c) an accessible area containing supernatants with solids contents on the order of 5 to 15 g/ℓ could not be found; (d) the need to maintain traffic flow around the dike precluded all test locations except at the overflow weir; and (e) water with a low solids content

(turbidity on the order of 200 to 300 JTU) was entering the weir structure through the joints between the stop-logs. Within the context of these restraints, it was decided to use as a filter suspension the supernatant that accumulated inside the overflow structure. Descriptions of the twenty tests conducted at this site are given in Table 15.

Penn 7

87. The Penn 7 disposal area in Toledo, Ohio, is in its third year of operation and has already been filled to about three-quarters of its capacity. The dike is about 12 ft (4 meters) high and of about one mile (1.6 kilometers) in perimeter. The effluent sluicing device consists of a cylindrical steel tube, and the discharge of supernatants is controlled by the height of stop-logs that form an overflow weir. At the time during which these tests were conducted, the water was being retained inside the diked area and there was no discharge of supernatants. Since previous experience with this disposal area (Krizek, Gallagher, and Karadi, 1974) indicated that the quality of water going over the weir was generally good and filtering would not normally be required, an alternate location for conducting these tests was selected about 400 ft (130 meters) from the inflow pipe. Because of channelization within the disposal area, the slurry reaching this point had a high concentration of suspended solids (2 to 10 g/ℓ, as determined gravimetrically in the laboratory). Sixteen tests were conducted on filter suspensions obtained by diluting this slurry with river water so that the suspended solids were about 0.5 g/ℓ. The slurry was diluted to simulate effluents from a much larger sedimentation basin. The list of all tests in this series, together with values of the variables for each, is given in Table 16.

Summary

88. In an effort to obtain the data required to evaluate the characteristics and performance capabilities of various filter media, over 300 laboratory and field filtration tests were conducted during the experimental phase of this research program. The laboratory test program consisted of (a) 204 tests on granular filter media, (b) 49 tests

Table 15

Summary of Field Filtration Tests at MOTSU

Test Number	Filter Medium	Head (cm)	Concentration (g/ℓ)
W1	FS	198	The concentration of suspended solids was between approximately 0.5 and 1.0 g/ℓ for all tests
W2	CS	198	
W3	CS	107	
W4	FG	107	
W5	FG	45	
W6	SG	107	
W7	SG	45	
W8	FA	107	
W9	FA	45	
W10	MA	107	
W11	MA	45	
W12	CS/FS	198	
W13	FG/FS	107	
W14	FG/FS	45	
W15	FA/FS	107	
W16	FA/FS	45	
W17	FG/FA	107	
W18	FG/FA	45	
W19	MA/FA	107	
W20	MA/FA	45	

Notes:

Filter Depth : 152 cm

Flow Direction : Vertical (downflow)

Type of Water : Saline (about 1.75% dissolved solids in the liquid phase)

Table 16

Summary of Field Filtration Tests at Penn 7

Test Number	Filter Medium	Head (cm)	Concentration (g/ℓ)
T1	FS	183	2.3 - 3.4
T2	FS	91	1.1 - 2.7
T3	FS	183	0.5
T4	CS	183	1.1 - 2.7
T5	CS	91	1.7 - 2.5
T6	CS	183	0.5
T7	FG	45	1.7 - 2.5
T8	CG	45	2.3 - 3.4
T9	SG	91	2.3 - 3.4
T10	SG	45	2.3 - 3.4
T11	FA	107	1.1 - 2.7
T12	FA	45	1.7 - 2.5
T13	FA	107	0.5
T14	MA	107	1.1 - 2.7
T15	MA	45	1.7 - 2.5
T16	MA	107	0.5
T17	CA	45	9.0 - 10.1
T18	CS/FS	183	9.0 - 10.1
T19	FG/FS	122	9.0 - 10.1
T20	FA/FS	122	9.0 - 10.1

Notes:

Filter Depth : 152 cm

Flow Direction : Vertical (downflow)

Type of Water : Fresh (about 0.11% dissolved solids in the liquid phase) on fibrous filter media, (c) 8 tests on nonconventional filter materials (straw, sawdust, wood chips, and wood shavings), (d) 12 supplementary tests on granular media (upflow, organic suspended solids, intermittent operation, and backwashing), and (e) one small series of vacuum filtration tests. Twenty field tests on granular filter media were conducted at disposal areas located in Wilmington, North Carolina, (saline water environment) and Toledo, Ohio, (freshwater environment).

89. The variables controlled during each laboratory tests were (a) type of water (salt or fresh), (b) nature of suspended solids (Grundite or kaolinite), (c) concentration of suspended solids (0.1 to 10 g/ℓ), (d) filter depth (5 or 8 ft), (e) direction of flow (vertical or horizontal), and (f) initial flow rate (high or low). The granular media ranged from fine sand to coarse gravel and from fine anthracite to coarse anthracite with effective grain sizes, D_{10}, between 0.38 and 5 mm. The fibrous media consisted of (a) synthetic fibers with random orientation (nonwoven), (b) woven synthetic fibers, and (c) wire screen.

90. Operating procedures for all tests were relatively consistent and included (a) the selection of variables, (b) the preparation of suspensions, (c) the preparation of filter columns, (d) sampling the filtrate, and (e) the control or measurement of discharge and head loss. The size-removal efficiency of the filter media was determined by particle counting, and the mass removal efficiency was determined directly by gravimetry or indirectly by turbidimetry. For the types of suspensions used, correlations were developed between turbidity readings and suspended solids concentration.

PART IV: DEVELOPMENT OF FILTER CRITERIA

91. The background investigation presented in Part II brought into perspective the necessity for developing filter systems to control the quality of effluents from dredged material confinement areas, and it indicated the possible beneficial use of granular and fibrous filter media as components of mechanized or nonmechanized filter systems. Accordingly, the experimental study described in Part III was undertaken to obtain information on the characteristics and performance capabilities of various granular and fibrous filter media. Presented in the following paragraphs are the results of (a) the series of laboratory tests on granular and fibrous media, (b) various supplementary laboratory studies, and (c) the field filtration tests. Based on these results, the observations that were made and conclusions that were drawn regarding the characteristics and performance capabilities of each filter medium are presented and discussed. Also included are guidelines and criteria that were developed to allow the optimum utilization of these media as active components of filter systems that are incorporated into the operation of dredged material confinement facilities.

Laboratory Tests on Granular Filter Media

92. A summary of the information obtained from tests on single- and dual-layer granular filter media is given in Tables 17 and 18, respectively. These tables, together with Table 11, provide an overall description of the conditions under which each test was conducted and the results that were obtained.

93. The data on head loss and discharge velocity allow the clogging tendency of each medium to be estimated for particular operational conditions. Initial discharge velocities were in the range of rapid sand filters (> 0.1 cm/sec), except for the fine sand (D_{10} = 0.4 mm) and dual media with a fine sand layer when tested under a low hydraulic head.

94. The mass-removal efficiency was computed either directly by

Table 17

Results of Laboratory Filtration Tests on Single-Layer Granular Media

Filter Medium	Type of Water	Initial Discharge Velocity (cm/sec)	Concentration (g/l)	Final Head Loss (cm)	Discharge Velocity Reduction (%)	Removal Efficiency (%)		Filter Coefficient (m^{-1})
						Mass	Size	
Fine Sand	Fresh	0.15	< 1	164	42	45-99.6	60-99	2.16
			> 1	169	53	22-71	25-50	0.71
		0.07	< 1	28	33	83-99.5	75-99	2.02
			> 1	84	68	60-88	50-98	1.55
	Salt	0.15	< 1	167	49	73-99.9	55-95	2.51
			> 1	175	98	40-65	48-90	0.46
		0.07	< 1	20	86	80-96	50-90	1.56
			> 1	87	50	60-88	52-90	0.81
Coarse Sand	Fresh	0.63	< 1	141	12	16-85	55-99	0.35
			> 1	170	35	3-34	20-60	0.15
		0.35	< 1	28	7	18-28	20-45	0.20
			> 1	66	47	2-82	15-75	0.21
	Salt	0.63	< 1	143	28	9-64	2-60	0.24
			> 1	150	57	20-25	18-55	0.17
		0.35	< 1	27	28	10-36	25-55	0.17
			> 1	83	50	20-25	20-47	0.18
Fine Gravel	Fresh	0.39	< 1	28	10	5-34	0-50	0.11
			> 1	21	5	0-24	0-45	0.10
	Salt	0.39	< 1	30	13	7-51	0-55	0.12
Coarse Gravel	Fresh	0.60	< 1	20	7	0-19	0-30	0.04
			> 1	12	6	0-15	0-28	0.04
Sand Gravel Mixture	Fresh	0.40	< 1	90	23	20-80	25-60	0.20
			> 1	94	11	1-21	0-45	0.10
		0.21	< 1	29	12	15-98	20-95	0.25
			> 1	32	10	1-24	0-40	0.11
	Salt	0.40	< 1	84	8	18-92	20-75	0.24
		0.21	< 1	32	16	21-80	20-75	0.25
Fine Anthracite	Fresh	0.27	< 1	52	21	62-94	50-85	1.15
			> 1	47	15	13-47	10-60	0.29
		0.10	< 1	36	46	59-98	50-98	1.39
			> 1	32	38	56-90	50-85	0.92
	Salt	0.27	< 1	77	14	47-98	55-75	1.27
			> 1	70	69	70-85	60-95	0.90
		0.10	< 1	27	40	94-99.7	60-98	2.45
Medium Anthracite	Fresh	0.57	< 1	55	8	28-75	20-50	0.47
			> 1	48	10	0-15	0-40	0.07
		0.25	< 1	17	20	20-72	20-63	0.61
			> 1	15	11	1-80	23-58	0.12
	Salt	0.57	< 1	64	7	27-69	18-62	0.39
		0.25	< 1	29	26	50-95	25-67	1.38
Coarse Anthracite	Fresh	0.60	< 1	22	9	8-35	0-42	0.17
			> 1	21	5	0-36	0-40	0.14
	Salt	0.60	< 1	14	3	6-32	0-51	0.16

Note: Concentrations designated as < 1 indicate tests conducted with 0.1 and 1 g/l of suspended solids

Concentrations designated as > 1 indicate tests conducted with 5 and 10 g/l of suspended solids

Table 18

Results of Laboratory Filtration Tests on Dual-Layer Granular Media

Filter Medium	Type of Water	Initial Discharge Velocity (cm/sec)	Concentration (g/ℓ)	Final Head Loss (cm)	Discharge Velocity Reduction (%)	Removal Efficiency (%) Mass	Removal Efficiency (%) Size	Filter Coefficient (m^{-1})
Coarse Sand over Fine Sand	Fresh	0.20	< 1	149	39	27-99	60-99	0.54/2.12
			> 1	130	95	42-75	28-52	0.28/0.72
		0.12	< 1	71	20	46-75	75-99	0.40/1.15
			> 1	95	88	33-63	40-98	0.25/1.47
	Salt	0.20	< 1	145	25	56-96	72-98	0.60/2.35
			> 1	140	90	35-80	45-95	0.25/1.18
		0.12	< 1	68	45	42-76	63-97	0.37/1.12
Fine Gravel over Fine Sand	Fresh	0.21	< 1	79	28	44-99	50-98	0.28/2.29
			> 1	85	29	7-30	28-58	0.12/1.25
		0.07	< 1	28	10	81-99	65-99+	0.38/2.81
			> 1	20	44	74-90	37-75	0.21/1.32
	Salt	0.21	< 1	95	18	42-98	62-99+	0.37/2.45
		0.07	< 1	25	7	97-99	58-99+	1.71/3.30
Fine Anthracite over Fine Sand	Fresh	0.12	< 1	82	15	50-98	75-99+	1.20/2.50
			> 1	91	10	2-46	50-78	0.25/0.82
		0.05	< 1	34	45	97-99	83-99+	1.71/4.11
			> 1	34	33	81-91	80-97	1.01/1.57
	Salt	0.05	< 1	39	25	94-99	87-99+	2.10/2.45
Fine Gravel over Fine Anthracite	Fresh	0.36	< 1	45	12	25-58	30-75	0.10/1.18
			> 1	37	14	0-15	10-62	0.10/0.32
		0.15	< 1	15	5	30-80	25-85	0.18/1.45
			> 1	17	10	1-89	3-78	0.17/1.28
	Salt	0.36	< 1	62	13	8-47	60-91	0.20/1.02
		0.15	< 1	8	6	15-75	60-95	0.70/1.85
Medium Anthracite over Fine Anthracite	Fresh	0.24	< 1	37	17	22-97	20-92	0.38/2.40
			> 1	38	15	2-35	10-49	0.12/0.42
		0.11	< 1	23	27	50-99	50-98	0.95/2.38
			> 1	27	10	1-24	5-35	0.15/0.67
	Salt	0.11	< 1	20	9	73-99	63-97	1.05/2.80

Note: Concentrations designated as < 1 indicate tests conducted with 0.1 and 1 g/ℓ of suspended solids
Concentrations designates as > 1 indicate tests conducted with 5 and 10 g/ℓ of suspended solids

gravimetric techniques or indirectly by the mass-turbidity correlations given in Appendix B. Size-removal efficiency is given as a range of values for the removal of suspended particles with an equivalent diameter of about 1.0 to 5.5μ, but limiting values do not necessarily correspond to the removal efficiency for the limiting particle sizes. It is seen that the ranges of values for mass- and size-removal efficiency are similar for the filter lengths employed.

95. Finally, average values for the filter coefficient, λ, are presented; this parameter is a measure of the efficiency of clarification and was computed on the basis that particle deposition in the filter is a first-order process in which suspended particle concentration decays exponentially with filter depth according to

$$C = C_o e^{-\lambda_o L} \tag{1}$$

where C and C_o are the effluent and influent concentrations, respectively; λ_o is the initial value of the filter coefficient at time equal to zero; and L is the filter depth. This relationship has formed the basis of mathematical models of clarification by depth filtration since 1937, and it has been validated under a wide range of experimental conditions (Ison, 1967; FitzPatrick and Spielman, 1973).

96. Because deposited particles alter the characteristics of the filtration action, the filter coefficient is admittedly not constant during the filtration process, and various relations have been proposed to determine its magnitude as a function of the amount of captured solids (Shekhtman, 1961; Mackrle, Dracka, and Svec, 1965; Maroudas and Eisenklam, 1965; Heertjes and Lerk, 1967; Ives, 1969; and Herzig, LeClerc, and Legoff, 1970). However, since the accurate determination of specific deposit (volume of deposited filter suspension per unit of bed volume) as a function of time and location along the filter column is extremely time consuming and relies on the development of largely untried experimental techniques, limited attention was given to direct deposit measurement in this study (specific deposit was measured for only about forty tests).

97. Appropriate plots of mass ratios for various depths of filter and times of operation were prepared according to Equation 1 and the filter coefficients, λ, were determined. Although some interpretation and judgment had to be employed, the computed coefficients are considered adequate to represent the clarification capabilities of each granular filter medium. It must be noted, however, that the filter coefficients presented herein have been computed for the total depth of the filter medium used in each test. It was observed that certain single-layer media (finer sands and finer anthracites) exhibited higher values of the filter coefficient for the top 15 to 45 cm.

Clarification characteristics
<u>of single-layer media</u>

98. The evaluation of the clarification capabilities of single-layer filter media is based mainly on the computed values of the filter coefficient and to a lesser extent on the observed mass and size-removal efficiencies (as determined by gravimetry and Coulter Counter spectra, respectively). Presented in Figure 19 is the variation of the filter coefficient with the effective grain size of the filter medium, and Figure 20 shows curves that are typical of the variation of the filter coefficient with time for four different media. The performance characteristics of granular media for different flow patterns (horizontal and downflow) and for different types of suspended solids (kaolinite and Grundite) are summarized in Figure 21 and 22, respectively. The filter coefficient values plotted in these figures represent average values for which the variation can be assessed by use of Table 17.

99. Based on the available results, the following observations regarding the clarification capabilities of single-layer granular media can be made:

a. The mass-removal efficiency of a filter medium with an effective grain size larger than 2.0 mm for sands and gravels and 3.5 mm for anthracites is very low. For example, according to Equation 1, to achieve a 66 percent efficiency a filter depth of 11 meters is required for a gravel with D_{10} = 2 mm and a depth of 6.5 meters is required for an anthracite with D_{10} = 3.8 mm. There is practically no dependence on the type of water, type of suspension, and concentration.

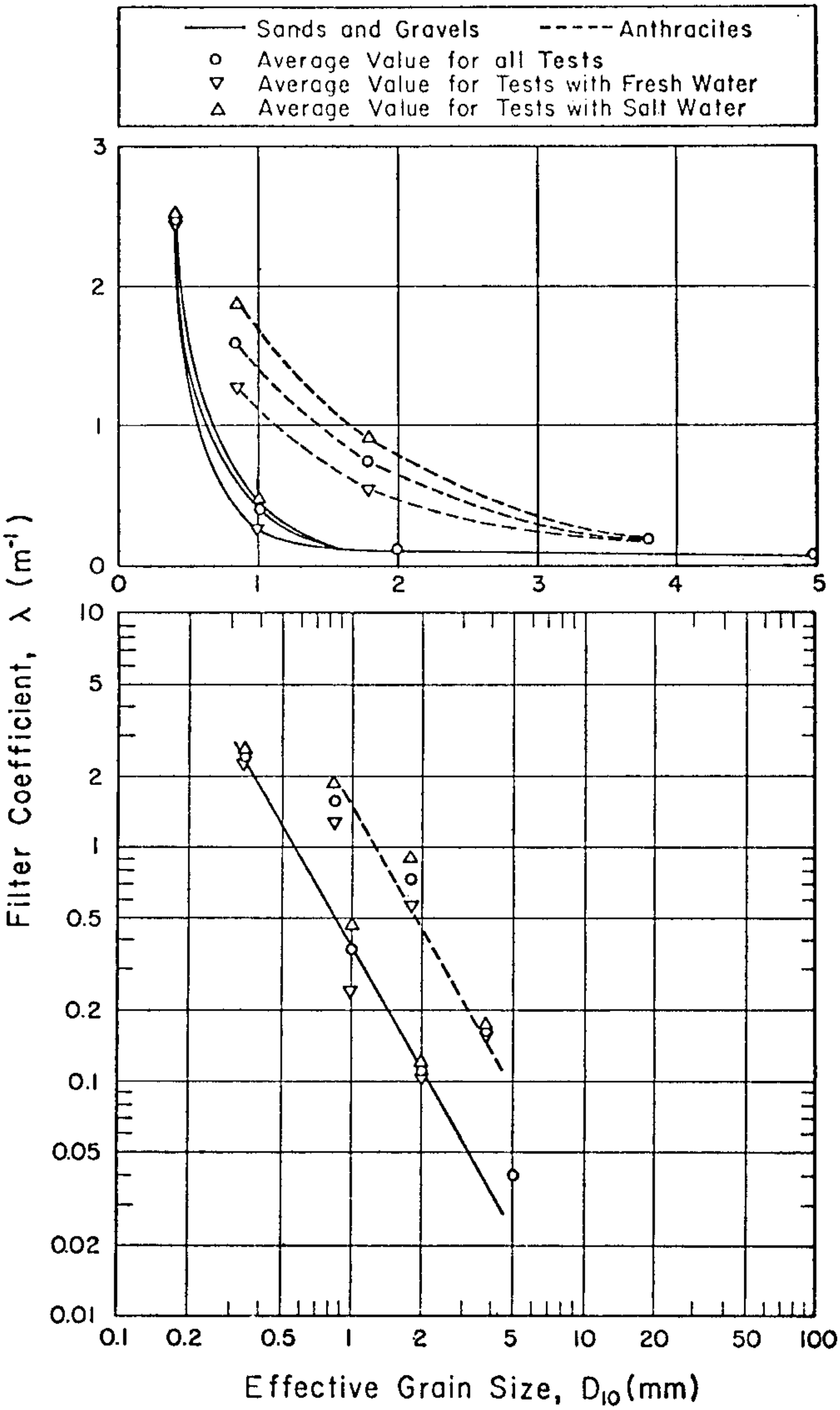

Figure 19. Variation of Filter Coefficient with Effective Grain Size

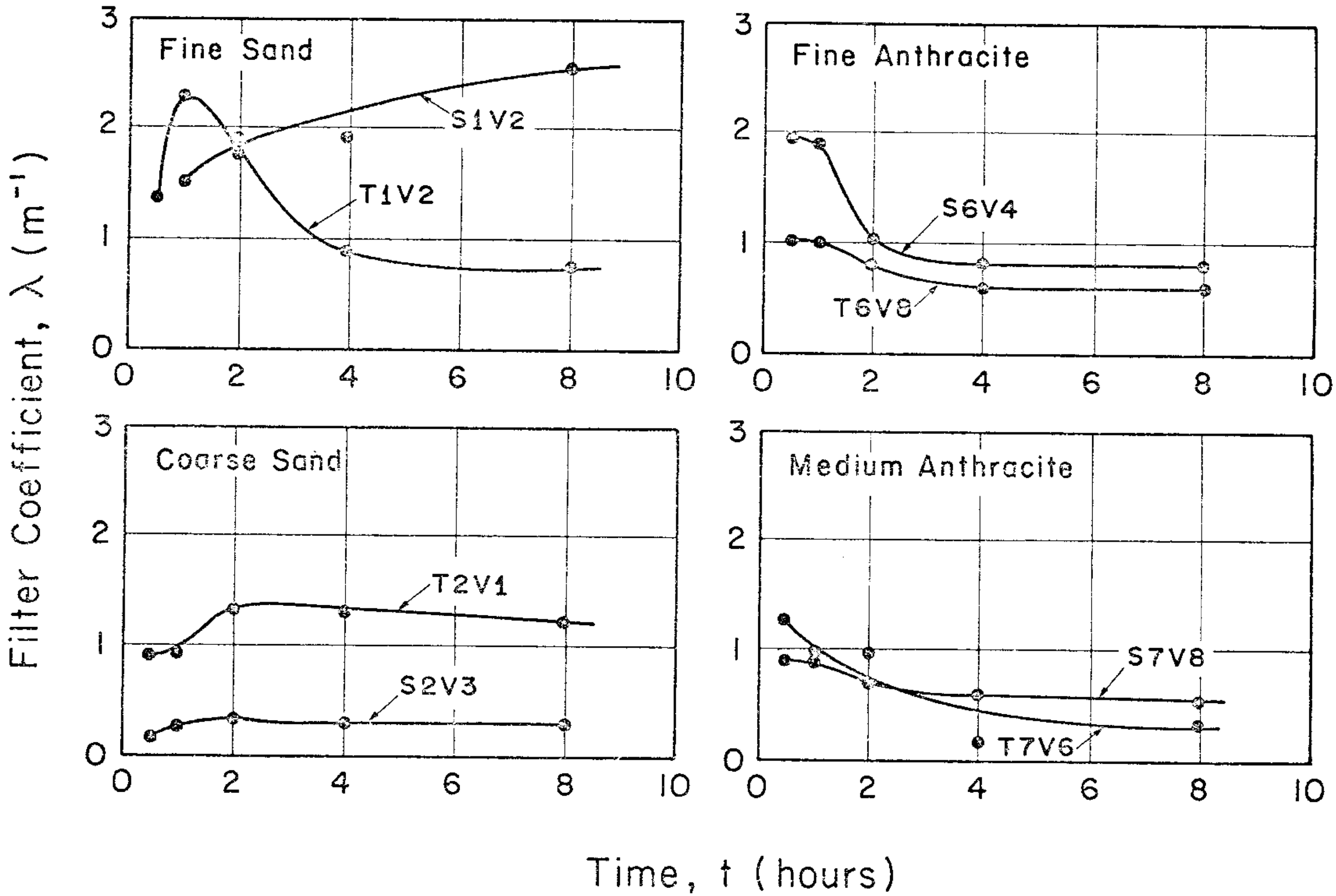

Figure 20. Typical Variations of Filter Coefficient with Time

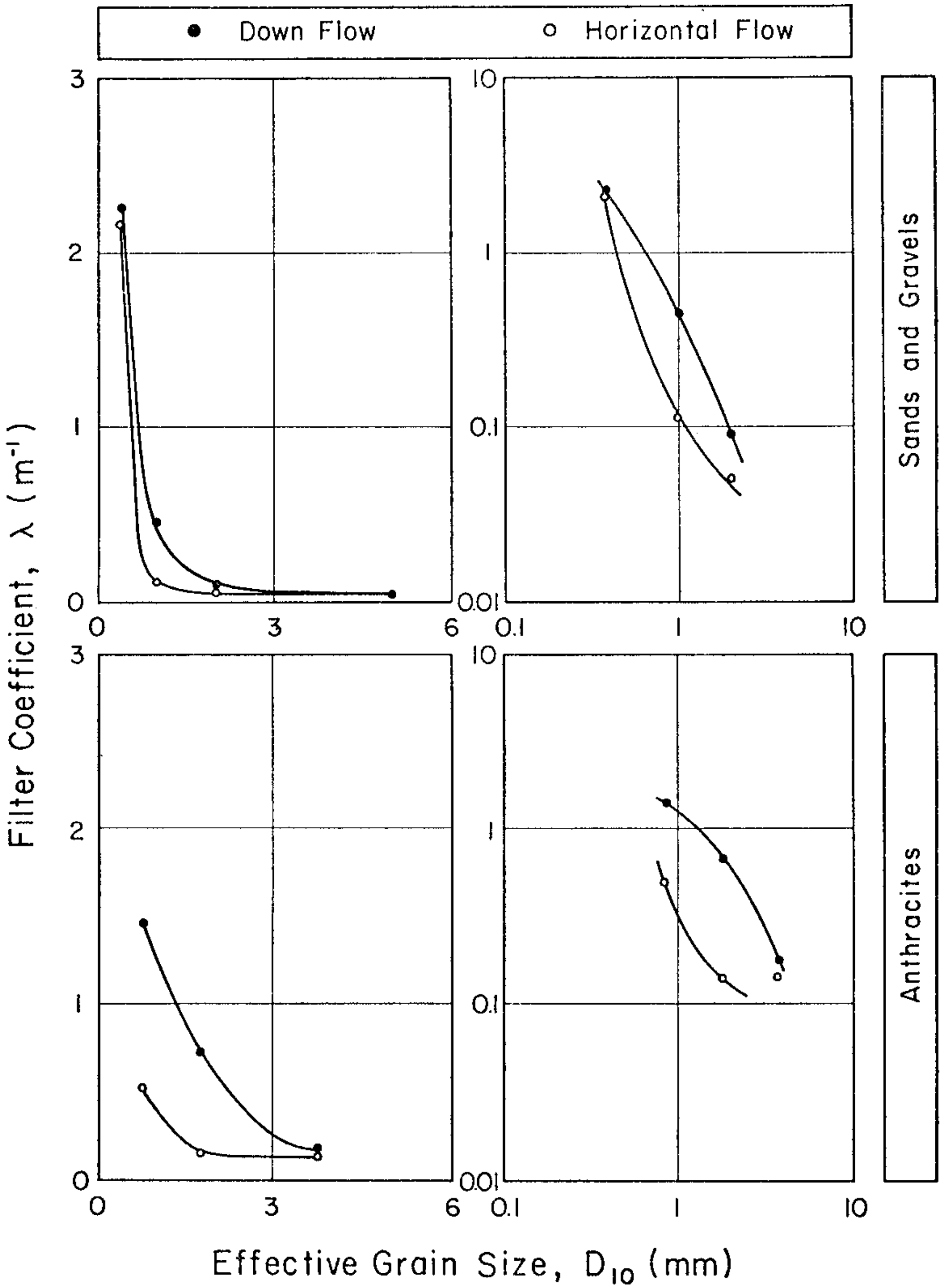

Figure 21. Performance of Granular Filter Media for Downflow and Horizontal Flow Directions

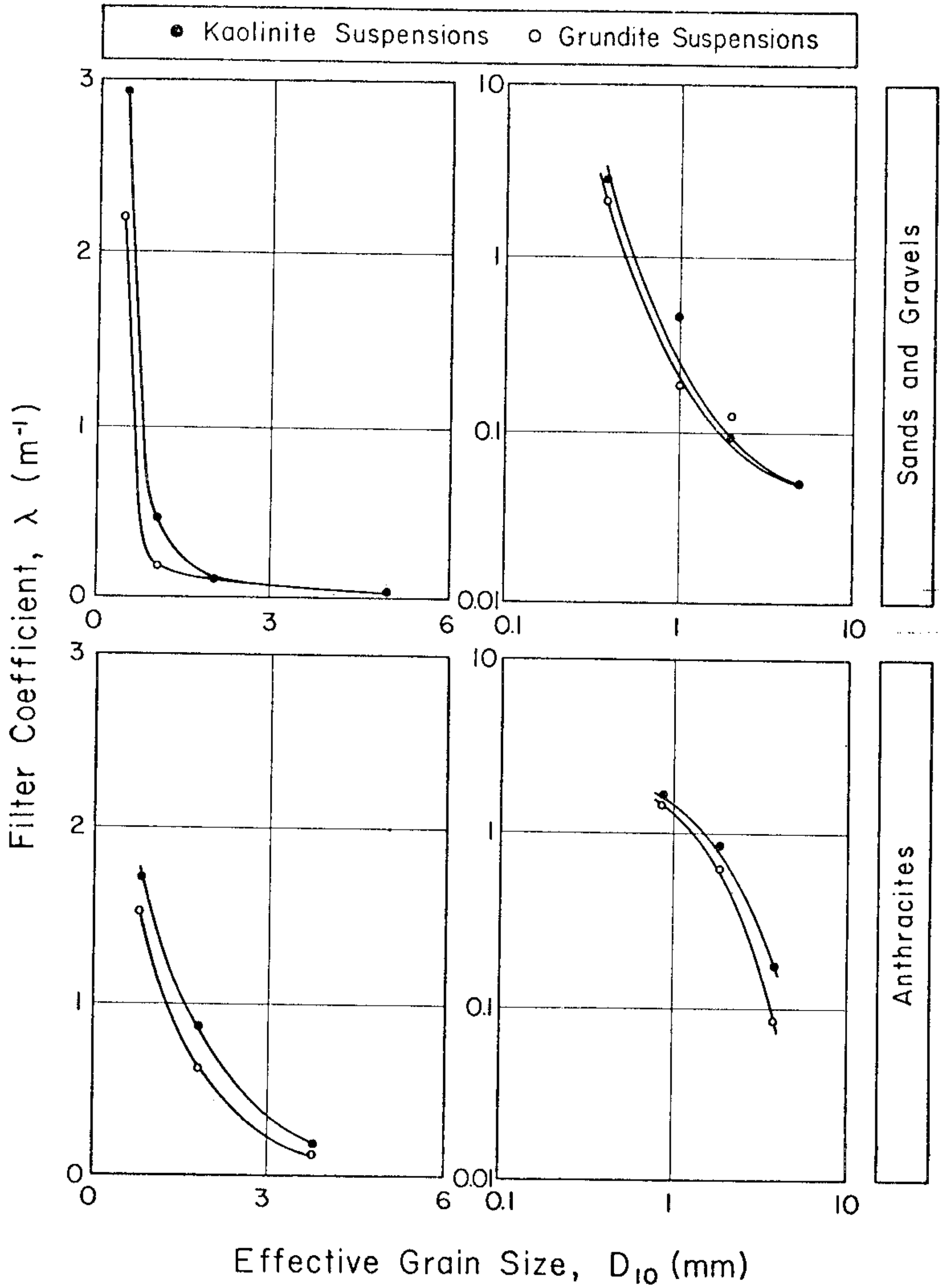

Figure 22. Performance of Granular Filter Media with Different Types of Suspensions

b. The removal efficiency of sands with D_{10} = 1 mm is limited. For example, to achieve a 66 percent efficiency, a filter depth of 2.5 meters is required.

c. Sand filters with $D_{10} < 1$ mm have good to excellent removal efficiencies, even with shallow filter depths, but their tendency to clog rapidly limits their usefulness as filter media.

d. Because of high angularity and more platelike grains, anthracites have a substantially higher removal efficiency than sands or gravels with the same effective grain size; accordingly, anthracite filters with D_{10} = 2 mm and D_{10} = 1 mm require depths of 1.6 and 1.0 meters, respectively, to achieve a 66 percent reduction in suspended solids.

e. Very interesting and somewhat unexpected is the fact that the behavior of sands and gravels in either saline or freshwater environments is the same for all practical purposes.

f. The behavior of anthracites is better in saline than in freshwater environments. Filter coefficients are about 50 percent higher for saline water environments, but this difference tends to disappear with increasing effective grain size and is virtually nonexistent for sizes larger than about 4 mm, thereby suggesting the unimportance of water chemistry on the collection process for coarse filters.

g. In general, the filter coefficient for sands reaches a maximum value quickly (in a matter of 1 to 2 hours) and gradually decreases to a constant value (for the next several hours at least). For finer sands (D_{10} = 0.4 mm), however, this is not always the case; the filter coefficient may increase for long periods.

h. Anthracites attain the maximum value of the filter coefficient at the beginning of the operation, and the value stabilizes after about 2 to 4 hours.

i. The performance of sands and gravels in filters with either horizontal or downward directions of flow is about the same. The efficiency of anthracites is substantially reduced during horizontal flow.

j. The different types of suspended solids (relatively stable inorganic clays) produced similar efficiency for all granular media. For Grundite suspensions the media have slightly lower filter coefficients than for kaolinite suspensions, although Grundite is a coarser suspension.

Clogging characteristics
of single-layer media

100. The clogging tendency of the granular media is reflected by the change in discharge velocity (or permeability) during operation. The final head loss across the filter relative to the overall head under which the filter operated also gives an indication of the extent of clogging. The following observations are based on the velocity and head loss data that are summarized in Table 17:

a. Gravels ($D_{10} > 2$ mm) do not clog readily and can retain their initial permeability for long periods of time (weeks or possibly months) under light or heavy loads of suspended solids (0.1 to 10 g/ℓ); hence, they might serve as ideal roughing filters.

b. Coarse sands ($D_{10} \approx 1$ mm) manifest fast clogging for heavy loads of suspended solids (more than 1 g/ℓ), but they can function well for moderate time periods (up to a few days) under light suspended solids loads (less than 1 g/ℓ).

c. Finer sands ($D_{10} \approx 0.4$ mm) suffer rapid clogging for practically any load of suspended solids; they apparently retain their operating efficiency for periods longer than a day only with suspended solids loads on the order of 0.1 g/ℓ or less.

d. Under comparable operating conditions, anthracites can function effectively for time periods that are similar to those experienced for sands and gravels.

e. As tested, the anthracites had significantly greater porosity than the sands or gravels (0.43 to 0.44 and 0.33 to 0.35, respectively); therefore, they had higher throughput rates under similar hydraulic heads.

Performance of dual-layer media

101. The assessment of dual-layer media is based on the results summarized in Table 18. The filter coefficient for each combination of media consists of two numbers corresponding to the first and second layer in the direction of flow, and the following observations can be made:

a. For loads of suspended solids less than 1 g/ℓ, all dual-layer media show good to excellent removal efficiency; for higher loads of suspended solids, the efficiency decreases, but not significantly.

b. For the case where fine sand was the bottom layer, the top-layer media show better efficiency and higher filter coefficient values than when tested as single-layer media; however, this should be attributed to the fact that, due to the existence of a sand layer with relatively low permeability, the flow rates were smaller and more time was allowed for interaction between filter grains and suspended particles.

c. For moderate loads of suspended solids (< 1 g/ℓ), the development of clogging is much slower in dual-layer media than in single-layer filters of the same media; this can be attributed to a more uniform distribution of retained solids along the depth of the dual-layer filter.

d. As expected, the combination of the best performing single-layer media (fine anthracite and fine sand) yields a dual-layer filter that has excellent removal efficiency (up to 99 percent) and a longer effective lifetime than any one of the components alone operating under a similar hydraulic head; similar improvement in performance is observed for the other dual-layer media.

Supplementary Studies

102. A limited number of supplementary tests were conducted to examine additional filter design and/or operating conditions. However, in view of the exploratory, rather than comprehensive, nature of these tests, caution should be exercised in extrapolating the observations, results, or conclusions of these tests to other than the specific test conditions.

Suspended organic matter

103. Fine and coarse sand and fine and medium anthracite filter media were used to determine the effect of suspended organic matter on the performance of granular media (Table 13). Waste activated sludge was employed for lack of a readily available fine organic particle suspension; but, even with a highly agitated suspension, particle sizes were still as large as 1 mm in diameter. After about one hour of operation, flow through the filter had practically stopped, and a cake about 1 to 1.5 cm thick had formed on the surface of the media. Since the sizes of the sludge particles were up to orders of magnitude larger than the sizes of the inorganic kaolinite or Grundite particles used in the

basic series of laboratory filtration tests, this surface cake was due largely to the gravity settling of sludge particles on the filter face. In this particular case it appears that the surface of the media was quickly clogged by capturing large-size organic particles and acted thereafter as a surface strainer to retain the majority of the inorganic particles. It can therefore be concluded that, for influents with very high concentrations of coarse suspended volatile solids (about 2 g/ℓ), the granular media tested will have a very short operating cycle or design life and will not operate as a depth filter. However, surface filters may use this rapid surface clogging phenomenon to advantage.

Upflow

104. Table 19 summarizes a series of tests that were conducted on four granular media in upflow and downflow modes with all other variables (water type, suspension concentration, available head, and filter depth) remaining constant. The performance observed for each filter medium was found to depend substantially on the direction of flow: specifically, for the four filter media tested (a) the mass-removal efficiency ranged from 10 to 70 percent for downflow and from 70 to 95 percent for upflow; (b) the change in discharge velocity after an eight hour run ranged from 10 to 58 percent for downflow and from 75 to 99 percent for upflow; (c) the distribution of retained solids along the filter was more uniform for upflow conditions; and (d) all filter media had practically clogged after 8 hours of operation in upflow conditions. It may therefore be concluded that, for the filter media tested, upflow conditions will improve substantially their mass-removal efficiency and increase the need for more frequent backwashing (or shorten the filter life in the absence of periodic cleaning).

Intermittent operation

105. As described in Table 13, two types of sand (D_{10} = 0.4 and 1.0 mm), and two types of anthracite (D_{10} = 0.8 and 1.8 mm) were tested under condition of intermittent operation. During the first 8-hour period of operation, the mass removal, head loss development, and reduction in discharge velocity followed patterns similar to tests T1V10, T2V10, T6V10, and T7V10 (Table 11), which had identical filtration

Table 19

Comparison of Results from Upflow and Downflow Tests

Test Number	Filter Medium	Head (cm)	Mass Removal Efficiency (%)		Change in Discharge Velocity (%)	
			Upflow	Downflow	Upflow	Downflow
T1V14	FS	107	95	70	99	43
T2V14	CS	107	70	10	90	10
T6V14	FA	45	92	70	75	58
T7V14	CA	45	83	25	75	11

Notes: Type of Water : Fresh
Suspension : Grundite
Concentration : 5 g/ℓ
Filter Depth : 152 cm

Table 20

Results of Backwashing Granular Filter Media

Filter Medium	Filtration Test		Backwashing		
	Direction of Flow	Estimated Retained Mass (g)	Average Discharge Velocity (cm/sec)	Estimated Mass Removed (g)	Removed Percentage of Total Mass
CS	Upflow	250	3.1	115	46
FA	Upflow	280	3.1	170	60
FA	Downflow	210	2.8	105	50
CA	Upflow	260	3.8	162	62
CA	Downflow	130	2.8	55	42

Notes: Type of Water : Fresh
Suspension : Grundite
Concentration : 5 g/ℓ

Table 21

Results of Laboratory Tests on Nonconventional Filter Media

Material	Mass Removal Efficiency (%)	Time for Clogging (hours)	Remarks
Hay	76 to 82	3.5	Yellow-brown filtrate
Sawdust	Unable to determine	0.25	--
Wood Chips	73 to 91	3.0	Brown-yellow filtrate
Wood Shavings	75 to 85	1.0	Yellow filtrate

conditions; this provided a good measure of the repeatability that was experienced. During the second and third periods of operation, the discharge velocities continued to decrease, and the fine sand filter could not even be operated for the third period because of complete clogging. Removal efficiencies for the second period of operation were inconsistent, and for the third period they were sometimes even negative (i.e., the effluents contained more suspended solids than the influents).

106. Based on these observations, it was concluded that, for highly concentrated influent suspensions (5 g/ℓ or more), the performance capabilities of the media tested do not improve with intermittent operation. It was hoped that a possible cementing of the deposit would take place under the partially saturated column conditions, but perhaps the rest period employed was too short. If the particles had been organic in nature, a rest period of perhaps two weeks would allow a microbial flora to unclog and rejuvenate the pores, as is commonly done in slow sand filters, but this benefit could not be expected in the case of filter influents composed of inorganic particles such as clays, since they are not substrates that can be degraded by microbial biota.

Backwashing

107. A number of filter media were backwashed with tap water under pressure to fluidize the bed, and the results obtained are summarized in Table 20. In general, about one half of the deposited volume of solids retained by the filter was removed with relatively high backwash rates (3 cm/sec). Backwashing was continued until the clarity of the effluent was visually established.

Nonconventional filter media

108. The results obtained from the laboratory filtration tests on nonconventional media (hay, sawdust, wood chips, and wood shavings) are summarized in Table 21. It is observed that (a) the mass-removal efficiency is very good (on the order of 70 to 90 percent); (b) the materials clog fast (15 minutes for sawdust to 3.5 hours for hay); (c) the effective service life of these media is substantially shorter than that for granular media under the same operating conditions (10 g/ℓ Grundite suspension in fresh water and constant head ranging from 100

to 200 cm); and (d) the effluents were heavily colored (yellow or yellow-brown), which may render them unacceptable for release to open waters. For sawdust and wood shavings (fine, tightly packed materials) face, rather than depth, clogging occurred, and it is believed that coarser sawdust or shavings would exhibit a much better performance.

Fibrous Filter Media

109. The performance capabilities of seven different fibrous media were evaluated by a series of laboratory filtration tests. The particular materials, equipment, test procedures, and range of variables investigated are described in Part III, together with a list of all tests conducted, and only the results of this test series and the conclusions drawn therefrom are presented herein. The major results obtained from tests of single-layer fibrous media are presented in Table 22, which summarizes the suspension type, concentration of suspended solids, water chemistry, discharge, head loss, flow time, and integrated removal efficiency for each test.

110. Basically, three parameters were used to evaluate the clogging and/or blinding tendency of a given filter medium: (a) the run duration; (b) the reduction in discharge velocity; and (c) the rate of head loss increase across the filter medium. The removal efficiency of each material was described as mass removal (gravimetric determination) and size removal (particle number count determination). Mass removal was determined for a limited number of samples taken during each test and the value reported in Table 22 is the average of the values obtained for a given test. Size-removal efficiency is given as a range of values for particle sizes between 1.0 and 5.5μ, but limiting values do not necessarily correspond to the removal efficiency for the limiting particle sizes.

111. The literature contains reports of limited efforts to develop a system of indexing that would facilitate a prediction of the behavior of an arbitrary fibrous medium. Recently, Rushton (1972a, 1972b) proposed a methodology to predict the clogging behavior of woven

Table 22

Results of Laboratory Filtration Tests on Fibrous Media

Filter Medium	Suspension	Type of Water	Concentration (g/ℓ)	Duration of Test (hours)	Discharge Velocity (cm/sec) Initial	Discharge Velocity (cm/sec) % Change	Head Loss (cm) Initial	Head Loss (cm) Final	Removal Efficiency (%) Mass	Removal Efficiency (%) Size	Filterability Index (10^4)
A SFR	Kaolinite	Fresh	1	4.5	1.46	40	3.56	--	2	ND	7
			10	6.0	1.46	80	3.30	4.83	ND	17-40	14
		Salt	1	4.0	1.46	45	1.02	2.54	4	10-17	5
			10	3.0	1.46	93	1.52	4.06	ND	11-20	32
	Grundite	Fresh	1	7.0	1.46	59	2.03	8.89	9	0-8	8
			10	IC	—	—	—	—	—	—	—
		Salt	1	5.5	1.46	88	2.54	5.84	14	21-31	21
			10	IC	—	—	—	—	—	—	—
B SFR	Kaolinite	Fresh	1	2.0	1.46	95	3.05	7.87	20	29-51	82
			10	2.0	1.46	93	2.29	10.16	ND	0-56	150
		Salt	1	6.5	1.46	87	4.57	8.38	ND	0-16	27
			10	5.0	1.46	90	4.83	7.87	19	9-28	37
	Grundite	Fresh	1	6.0	1.46	87	7.87	11.43	5	12-35	44
			10	IC	—	—	—	—	—	—	—
		Salt	1	3.0	1.46	91	12.45	16.00	29	0-14	161
			10	IC	—	—	—	—	—	—	—
C SSW	Kaolinite	Fresh	1	3.0	2.05	37	23.88	26.67	16	2-20	64
			10	4.0	1.46	32	14.48	14.48	2	1-26	32
		Salt	1	NT							
			10	IC	—	—	—	—	—	—	—
	Grundite	Fresh	1	4.0	1.46	42	13.72	—	10	1-8	27
			10	NT							
		Salt	1	4.0	1.46	46	11.18	—	15	ND	22
			10	IC	—	—	—	—	—	—	—
D SFW	Kaolinite	Fresh	1	0.5	1.46	92	16.76	24.64	6	0-9	1926
			10	IC	—	—	—	—	—	—	—
		Salt	1	NT							
			10	IC	—	—	—	—	—	—	—
	Grundite	Fresh	1	IC	—	—	—	—	—	—	—
			10	IC	—	—	—	—	—	—	—
		Salt	1	NT							
			10	IC	—	—	—	—	—	—	—
E SFW	Kaolinite	Fresh	1	IC	—	—	—	—	—	—	—
			10	IC	—	—	—	—	—	—	—
		Salt	1	NT							
			10	IC	—	—	—	—	—	—	—
	Grundite	Fresh	1	IC	—	—	—	—	—	—	—
			10	IC	—	—	—	—	—	—	—
		Salt	1	NT							
			10	IC	—	—	—	—	—	—	—
F SFW	Kaolinite	Fresh	1	NT							
			10	3.0	1.46	90	1.52	2.79	8	7-30	14
		Salt	1	NT							
			10	2.0	1.46	91	4.57	6.10	15	10-27	62
	Grundite	Fresh	1	2.0	1.46	92	4.57	7.37	12	8-16	107
			10	IC	—	—	—	—	—	—	—
		Salt	1	NT							
			10	IC	—	—	—	—	—	—	—
G SFW	Kaolinite	Fresh	1	2.0	1.46	91	4.57	8.38	4	0-25	95
			10	NT							
		Salt	1	NT							
			10	0.67	1.46	90	42.16	43.69	25	4-37	1674
	Grundite	Fresh	1	NT							
			10	IC	—	—	—	—	—	—	—
		Salt	1	NT							
			10	IC	—	—	—	—	—	—	—

Notes: IC = Immediate Clogging ND = Not Determinable NT = Not Tested fibrous media. However, this methodology applies only to media with standard pore configurations (size and weave pattern), and it can not be applied to nonwoven cloths that have randomly oriented fibers with no standard pore sizes.

112. Because nonwoven cloths exhibited the best performance in this experimental program, Rushton's technique for evaluating the performance was not adopted. Instead, a simple formula was used to obtain a number that described the performance of each medium. Ives (1971) reviewed the concepts underlying the filterability indices that have been proposed during the past 30 years to describe granular filter performance. Although none have found wide applicability or acceptance, an index originally proposed by Hudson (1959) has been developed to the point where a commercial device marketed in the United Kingdom was designed to determine this filterability index, FI, which is given by

$$FI = \frac{HC}{v\ t\ C_o} \tag{2}$$

where H is the head loss across a granular layer; v is the discharge velocity; t is a certain time period; and C and C_o are the effluent and influent concentrations, respectively.

113. It can be seen that FI is dimensionless and independent of filter depth. High (poor) values are obtained for high head loss or poor filtrate, and low (good) values result for high flow rates, long run times, or low effluent concentrations. Although Hudson's filterability index was originally developed for granular media, its application here to fibrous media (Table 22) yielded FI values that were consistent with the performance of each medium, as described by the values of other parameters listed in Table 22. However, these numbers should be considered only as a guide to the performance of a given filter medium; they do not yield information on the time variation of efficiency, blinding versus cake build-up on the medium, or the nature of the breakthrough (if it occurs). Nevertheless, the filterability index can constitute an effective basis for rapidly comparing various filter media or operating conditions. In Figure 23 the size-removal efficiencies

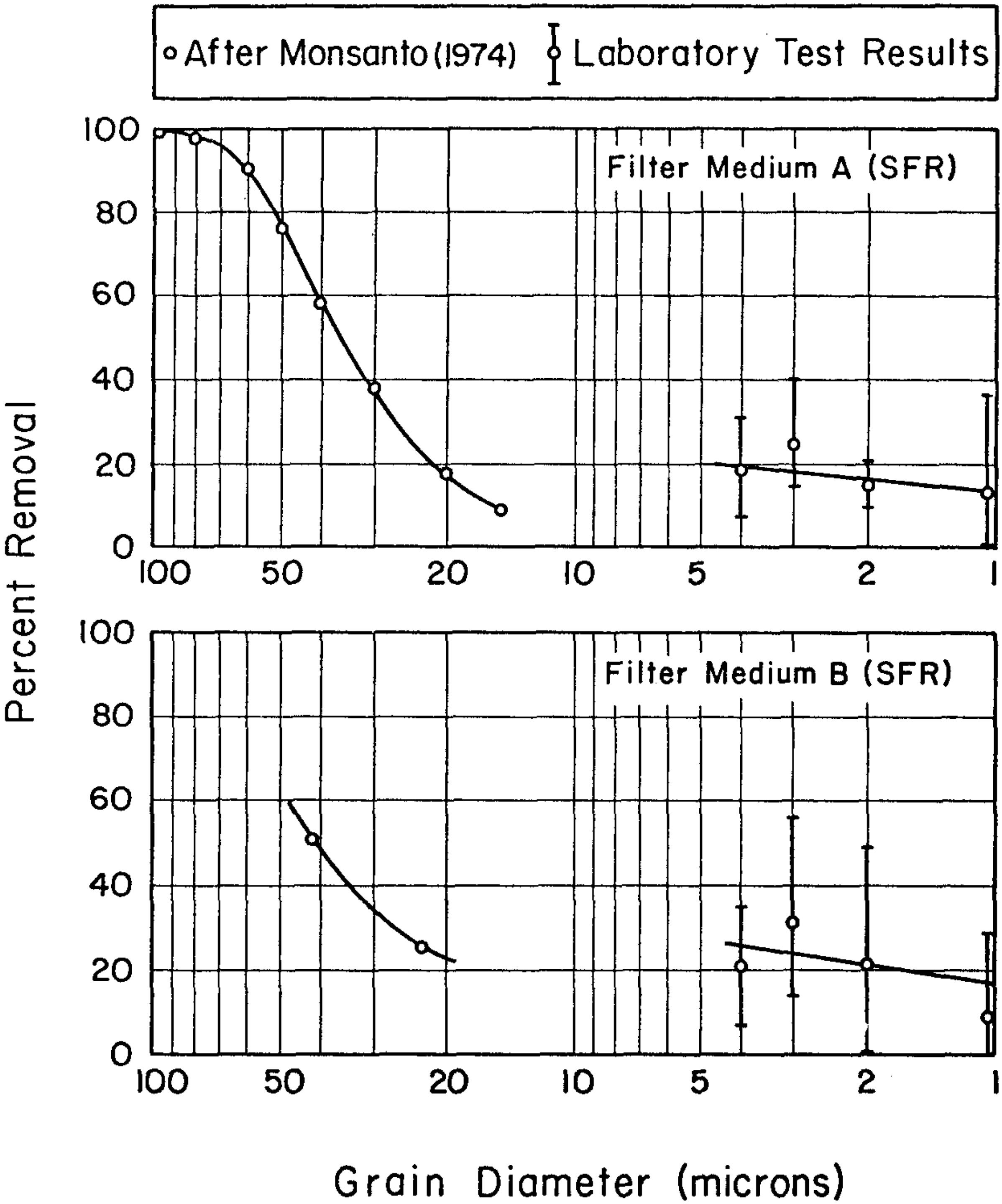

Figure 23. Size Removal Efficiency of Nonwoven Fibrous Filter Media

obtained for the nonwoven synthetic fiber media (A-SFR and B-SFR) are plotted with data obtained by the manufacturer (Monsanto, 1974).

114. Based on the results presented in Table 22 and Figure 23, the following observations can be made.

Synthetic nonwoven fibrous media

a. These media generally showed the best overall behavior of any class of fibrous media tested. For run durations ranging from 2 to 7 hours, the mass-removal efficiency was found to range from 2 to 29 percent and the size-removal efficiency for 1.0 to 5.5μ diameter particles ranged from nil to 56 percent.

b. The Monsanto E2B cloth (A-SFR) normally had longer runs before clogging, smaller head loss build-up, slightly lower removal efficiencies, and significantly smaller filterability index values than the Celanese Mirafi (B-SFR).

c. Neither medium performed well with suspensions having high influent solids concentrations. Immediate clogging was experienced for Grundite suspensions, and the performance was even poorer for kaolinite suspensions (indicated by high filter number).

d. For low concentration suspensions, the performance of both media was good without regard to suspension type or water chemistry.

Wire screens

a. Based on values of the filterability index, the performance of the wire screen tested (5μ opening size) appears to be similar to that of nonwoven synthetic fiber media for similar test conditions.

b. Immediate clogging was experienced for high concentration suspensions.

c. At low concentrations the mass-removal efficiency was about 15 percent and the size-removal efficiency ranged from 1 to 26 percent. The rate of change in flow rate with time was much smaller than for nonwoven media and there was no appreciable increase in head loss with time.

Synthetic woven fibrous media

a. In general, all four media tested had poor performance (immediate clogging or very short run time) under all conditions of suspension concentration and water chemistry.

b. Medium F-SFW (National Filter Media, pore size of 50μ) can be considered an exception for the case of kaolinite suspensions, for which it had a mass-removal efficiency of 8 to 15 percent and sustained a run time of 2 to 3 hours.

Multiple-layer fibrous media

115. Synthetic, nonwoven fibrous media in multiple (three and five) layers were tested using 1 g/ℓ Grundite suspension in fresh water at initial flow rates of about 1.4 cm/sec. The Monsanto cloth (Medium A-SFR) clogged quickly (the duration of the tests was about 0.2 hours), but it had a very high mass-removal efficiency (about 80 percent). The Celanese cloth (Medium B-SFR) clogged less rapidly (the duration of the tests ranged from 0.5 to 1 hour), but it had a substantially lower mass-removal efficiency (about 12 percent).

Field Filtration Tests

116. The results obtained from the field filtration tests on single and dual-layer granular filter media are presented in Tables 23 and 24 and in Figure 24. More detailed information concerning the test conditions is given in Tables 15 and 16. The methods adopted to summarize and interpret the data were similar to those used for the laboratory tests, and the following observations are made on the basis of these results:

a. As indicated by the values of the filter coefficient, sands or gravels and anthracites with effective grain sizes of 2.0 and 3.5 mm, respectively, have very low removal efficiencies and consequently very limited clarification capabilities.

b. Removal efficiency improves with decreasing effective grain size and becomes excellent for fine sand and fine anthracite; however, for the tests in a saline water environment (MOTSU), the efficiency is low, even for the fine-grained filter media.

c. Anthracites have a higher removal efficiency than sands or gravels of the same effective grain size. This difference is substantial for the freshwater tests, but it is less pronounced for the saltwater tests.

d. Observations (b) and (c) are quite unexpected; for similar types of suspended solids, it would be expected that

Table 23

Results of Field Filtration Tests at Penn 7

Test Number	Filter Medium	Effective Grain Size (mm)	Duration of Test (hours)	Discharge Velocity (cm/sec)			Removal Efficiency (%)	Filter Coefficient (m^{-1})
				Initial	Final	% Change		
T1	FS	0.38	2.0	0.14	0.01	93	75-90	1.30
T2	FS	0.38	4.0	0.07	0.01	85	95-99	2.10
T3	FS	0.38	4.5	0.10	0.07	30	90-99	2.5
T4	CS	1.0	4.0	0.34	0.01	97	20-25	0.20
T5	CS	1.0	2.5	0.20	0.01	95	20-50	0.40
T6	CS	1.0	4.5	0.36	0.32	11	40-50	0.40
T7	FG	2.0	4.5	0.41	0.41	0	10-15	0.11
T8	CG	5.0	4.5	0.78	0.71	9	0-10	0.04
T9	SG	1.0	4.5	0.48	0.37	23	5-30	0.10
T10	SG	1.0	4.5	0.24	0.16	33	10-20	0.10
T11	FA	0.85	4.0	0.31	0.03	90	60-90	0.90
T12	FA	0.85	4.0	0.14	0.03	79	90-95	2.00
T13	FA	0.85	4.5	0.20	0.19	5	50-90	0.80
T14	MA	1.80	4.0	0.37	0.27	27	20-40	0.30
T15	MA	1.80	4.0	0.22	0.21	5	20-80	0.40
T16	MA	1.80	4.5	0.34	0.33	3	30-80	0.52
T17	CA	3.80	4.0	0.47	0.46	2	0-10	0.02
T18	CS/FS	1.0/0.38	1.0	0.20	0.01	95	-	-
T19	FG/FS	2.0/0.38	1.0	0.23	0.01	96	-	-
T20	FA/FS	0.85/0.38	1.0	0.18	0.01	94	-	-

Table 24

Results of Field Filtration Tests at MOTSU

Test Number	Filter Medium	Effective Grain Size (mm)	Duration of Test (hours)	Discharge Velocity (cm/sec)			Removal Efficiency (%)	Filter Coefficient (m^{-1})
				Initial	Final	% Change		
W1	FS	0.38	5.5	0.12	0.06	50	60-65	0.65
W2	CS	1.0	5.0	0.35	0.23	33	35-50	0.33
W3	CS	1.0	5.0	0.16	0.03	78	45-55	0.45
W4	FG	2.0	4.5	0.82	0.82	0	5-10	0.06
W5	FG	2.0	5.0	0.40	0.40	0	30-40	0.25
W6	SG	1.0	5.5	0.62	0.59	4	20-25	0.17
W7	SG	1.0	5.0	0.25	0.20	20	25-30	0.27
W8	FA	0.85	5.5	0.21	0.20	5	35-50	0.42
W9	FA	0.85	5.0	0.08	0.04	50	50-60	0.61
W10	MA	1.80	5.5	0.40	0.40	0	30-40	0.32
W11	MA	1.80	5.0	0.22	0.16	27	30-35	0.30
W12	CS/FS	1.0/0.38	4.5	0.21	0.14	33	80-85	0.80,2.00
W13	FG/FS	2.0/0.38	5.0	0.22	0.17	23	70-80	0.40,1.50
W14	FG/FS	2.0/0.38	4.5	0.08	0.04	50	80-85	0.40,2.00
W15	FA/FS	0.85/0.38	5.0	0.19	0.18	5	60-85	2.00,1.20
W16	FA/FS	0.85/0.38	4.5	0.05	0.03	40	75-90	1.50,1.50
W17	FG/FA	2.0/0.85	5.0	0.58	0.58	0	25-50	0.10,0.50
W18	FG/FA	2.0/0.85	5.0	0.17	0.09	47	45-80	0.10,0.70
W19	MA/FA	1.80/0.85	5.0	0.31	0.31	0	60-70	0.20,0.65
W20	MA/FA	1.80/0.85	5.0	0.16	0.08	50	60-80	0.65,0.70

Note: For tests W12 through W20 (dual layer media) the filter coefficients given correspond to the top and bottom layer respectively.

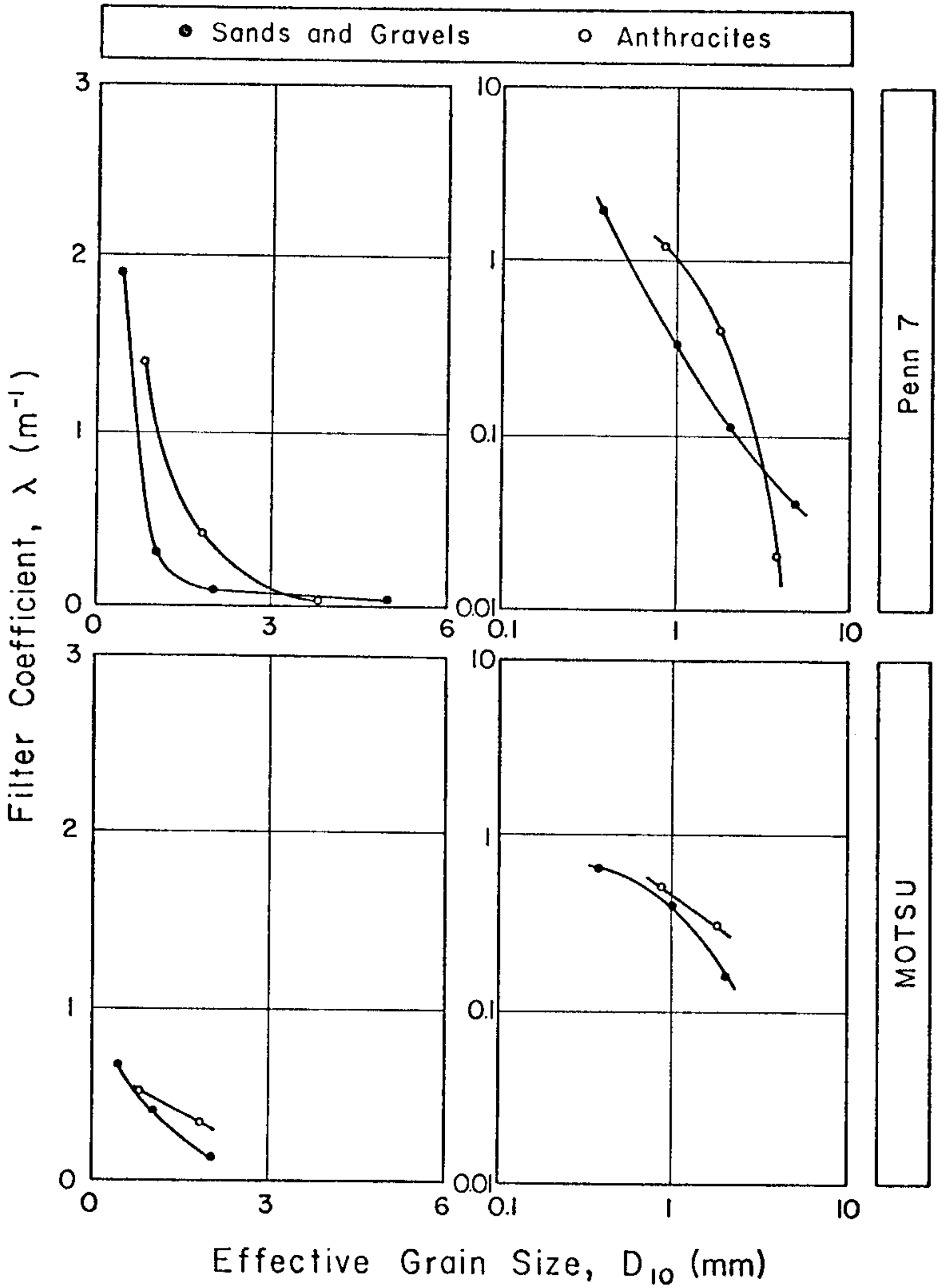

Figure 24. Variation of Filter Coefficient with Effective Grain Size for Field Filtration Tests

media tested in a freshwater environment should have lower filter coefficient values than when tested in a saline water environment. The observed reverse pattern can possibly be explained by the difference in the water environments used for the laboratory and the field tests and by the fact that the suspended solids in the freshwater field environment were larger in size and had a different surface chemistry than those in the saltwater environment.

e. Higher overall hydraulic heads and consequently higher discharge velocities result in lower mass removal efficiencies, especially for the fine-grained media (sometimes there is as much as 50 percent reduction).

f. For high concentrations of suspended solids (2 to 10 g/ℓ), the fine and coarse sand, the fine anthracite, and all dual-layer media tested clogged quickly; the discharge velocities were reduced by more than 90 percent in a period of 1 to 4 hours, and a cake about 0.5 to 1 cm thick formed on the top of the filter.

g. Except for the above-mentioned cases, media tested did not show clogging tendencies for either high or low loads of suspended solids.

h. For low concentrations of solids (< 1 g/ℓ), the dual-layer media showed high removal efficiency and low clogging tendency.

Comparison of Field and Laboratory Results

117. The objectives of the field filtration tests were to evaluate the field performance of granular media that were tested in the laboratory and to provide guidance for extending the findings of the laboratory tests to the design of filter systems for disposal area supernatants. As explained in Part III, the field suspensions were different from those used in the laboratory tests. Whereas the laboratory suspensions consisted only of nonvolatile suspended solids with concentrations ranging from 0.1 to 10 g/ℓ (except for a limited number of tests in which a large amount (2 g/ℓ) of organic matter was added to the suspension), the composition and concentration of the field suspensions were dictated in large part by the operating conditions at the time of the tests. In summary, nonvolatile suspended solids varied from 0.5 to 10 g/ℓ and volatile suspended solids varied from 3 to 6 percent of the total solids on a dry

weight basis. A careful review of the results of the laboratory and field filtration tests allowed the following observations to be advanced:

- a. The clarification capabilities exhibited by the granular media, as judged by their removal efficiency and filter coefficient, were similar for both field and laboratory tests.
- b. Coarse media (gravels with $D_{10} > 2.0$ mm and anthracites with $D_{10} > 3.5$ mm) did not show any tendency to clog in either field or laboratory tests.
- c. For low concentrations of suspended solids (< 1 g/ℓ), all of the finer media exhibited similar clogging patterns, with clogging taking place slightly faster in the field tests.
- d. Fine sand, fine anthracite, and dual-layer media that had fine sand or anthracite as components clogged much faster in the field than in the laboratory.
- e. The difference in clogging behavior for the finer granular media can be explained by considering the organic content of the suspensions. Organics, having larger dimensions than suspended nonvolatile solids, were captured quickly by the filter media and, as a result, the top layer of the medium clogged and acted as a surface filter rather than as a depth filter. It is believed that geometric factors, such as straining or pore blocking, are more significant than surface chemical factors in the capture of large-size suspended organics.

Filter Media Design Concepts

118. The performance characteristics and capabilities of a number of granular and fibrous filter media were determined with the help of an extensive experimental study, and the results presented herein lead to the following guidelines and criteria for the use of such media as components of filter systems for supernatants from dredged material disposal areas. Quantitative details on the performance of filter systems will be presented in the following parts.

- a. For a given effective grain size, D_{10}, the following equations can be used to estimate the filter coefficient (see Figure 19):

  Sands and Gravels: $\lambda = 0.40\ D_{10}^{-1.84}$ (3a)

Anthracites: $\lambda = 1.66\ D_{10}^{-1.84}$ (3b)

where D_{10} is expressed in mm and λ is found in m^{-1}.

b. For a known filter coefficient and removal efficiency, Equation 1 can be used to estimate the required depth of filter.

c. Sands or gravels and anthracites with effective grain sizes larger than about 2.0 and 3.5 mm, respectively, should not be used for clarification purposes, but rather as roughing filters to dissipate some velocity head and provide crevices for trapping large, light particles.

d. Sands and anthracites with effective grain sizes ranging from 0.8 to 2.0 mm and from 2.0 to 3.5 mm, respectively, can be used effectively for clarification only when large filter depths are employed. For example, to achieve a 90 percent removal efficiency, a filter composed of a sand with an effective grain size of 1.5 mm should have a depth of 12 meters; for an anthracite with an effective grain size 3 mm, the filter depth should be 10 meters. Although these media can be used to clarify waters with low concentrations of suspended solids (0.1 to 1 g/ℓ), high loadings should be avoided.

e. Sands and anthracites with effective grain sizes smaller than 0.8 and 2.0 mm, respectively, have good clarification capabilities. The filter depth necessary to produce effluents of a desired quality can be estimated easily by entering values for the filter coefficient, λ, obtained from Figure 19 into Equation 1. For heavy loads of suspended solids, these materials will require frequent or continuous cleaning by backwashing or other methods, and thus their applicability to filter systems requiring little or no maintenance appears to be limited without high capital investment. However, these media are considered to be the most promising candidates for use as components of mechanized or nonmechanized depth filtration systems.

f. For cases where disposal area supernatants contain large amounts of suspended volatile solids, fine-grained granular media can be used as slow sand filters in which biological action is promoted in a "Schmützdecke" layer that is periodically renewed by allowing the filter to lay idle. Such filters require periodic maintenance of the top layer.

g. Dual-layer granular media composed mainly of fine and coarse sands and fine and medium anthracites can be used very effectively to clarify low concentration suspensions. For high concentration suspensions, however, clogging will likely be pronounced and backwashing schemes will be necessary.

h. Fibrous media, in general, should be used as components of mechanized systems that provide for continuous cleaning of the surface of the medium. As an exception, nonwoven synthetic fiber media (like the Monsanto E2B cloth) can be used in nonmechanized multi-layer systems for low concentrations of suspended solids, and they may also be incorporated into a self-cleaning filter design.

PART V: CONCEPTS FOR FILTERING SYSTEMS

119. Virtually all conventional granular media filtration units are mechanized to a large extent. The mechanization, which may vary widely in the degree of complexity, consists of means for pumping feed waters, controlling flow rates, and cleaning the filter media; and these mechanisms result in substantial initial capital investment, as well as operating and maintenance costs. Conventional granular media systems often require as much as two-thirds of the total amortized capital, maintenance, and operation costs for pumping, valves, and other instrumentation requiring only negligible power. Conventional systems also require adequate facilities for the disposal of wash waters.

120. Nonmechanized granular media filtration systems appear to be a promising alternative for the clarification of disposal area supernatants. A few such systems have been designed (see Part II) and constructed, but their performance has been poorly documented (if at all); designs were highly empirical and usually had little or no rational basis. Described herein are three different systems that appear to be applicable to the filtration of effluents from dredged material disposal areas: pervious dikes, sandfill weirs with or without backwash, and granular media cartridges. The information provided for each system includes (a) filter media, (b) system configuration, (c) operating conditions and performance capabilities, and (d) guidelines for the design and operation of the system.

Pervious Dikes

121. The vast majority of disposal area confinement facilities are formed by enclosing a tract of land or a portion of a lake or harbor by a dike. It is therefore appropriate to consider the development of a filter system in the form of a pervious dike that, if properly positioned and dimensioned, could effectively clarify disposal area supernatants.

Filter design concepts

122. In the conceptual development of a pervious dike, the

following limitations should be taken into consideration:

- a. If the system malfunctions (that is, if it does not produce the required quality of effluents), corrective measures, if possible, are extremely expensive.
- b. There should be no face clogging of the filter media; removed suspended solids should be distributed through the depth of filter medium. Although Trzaska (1972) has developed a strategy to select a media distribution such that a uniform deposit is guaranteed, the method has been applied only to the design of industrial filters.
- c. The dike must not clog or lose its efficiency before the design life of the disposal area has been exhausted.
- d. A pervious dike is not a reusable filter.

123. Since the main disadvantage of fine-grained material is rapid clogging, pervious dikes should use coarse-grained deep beds that have low clarification efficiency per unit depth (that is, a low filter coefficient) but maintain high permeability throughout the filter life; longer depths must be used to provide the needed clarification. The key to the success of the system is to select a media size that will not face-clog or lose its ability to achieve the required clarification before the design life of the containment facility is reached.

124. Alternative designs. Pervious dikes can be designed in a number of different ways, two of which appear to be the most promising for the purposes outlined herein. Figure 25a shows a dike that is constructed totally of the selected filter medium; it is equipped with a strong drain at the outside toe; and its slopes are protected with layers of gravel and riprap. Figures 25b and 25c illustrate dikes utilizing impervious layers to guide the flow of water or impervious sectors to prevent short circuiting. It is desirable that a pervious dike operate under a hydraulic head that is as high as the size of the dike allows, because the highest possible hydraulic gradients are realized for such a condition and the highest possible flow rates are achieved. However, if care is not taken, such an operating condition will contaminate all of the filter medium with retained solids during the first operating cycle of the dike (say, the first dredging season), and this might seriously impair retention efficiency during the remaining intended

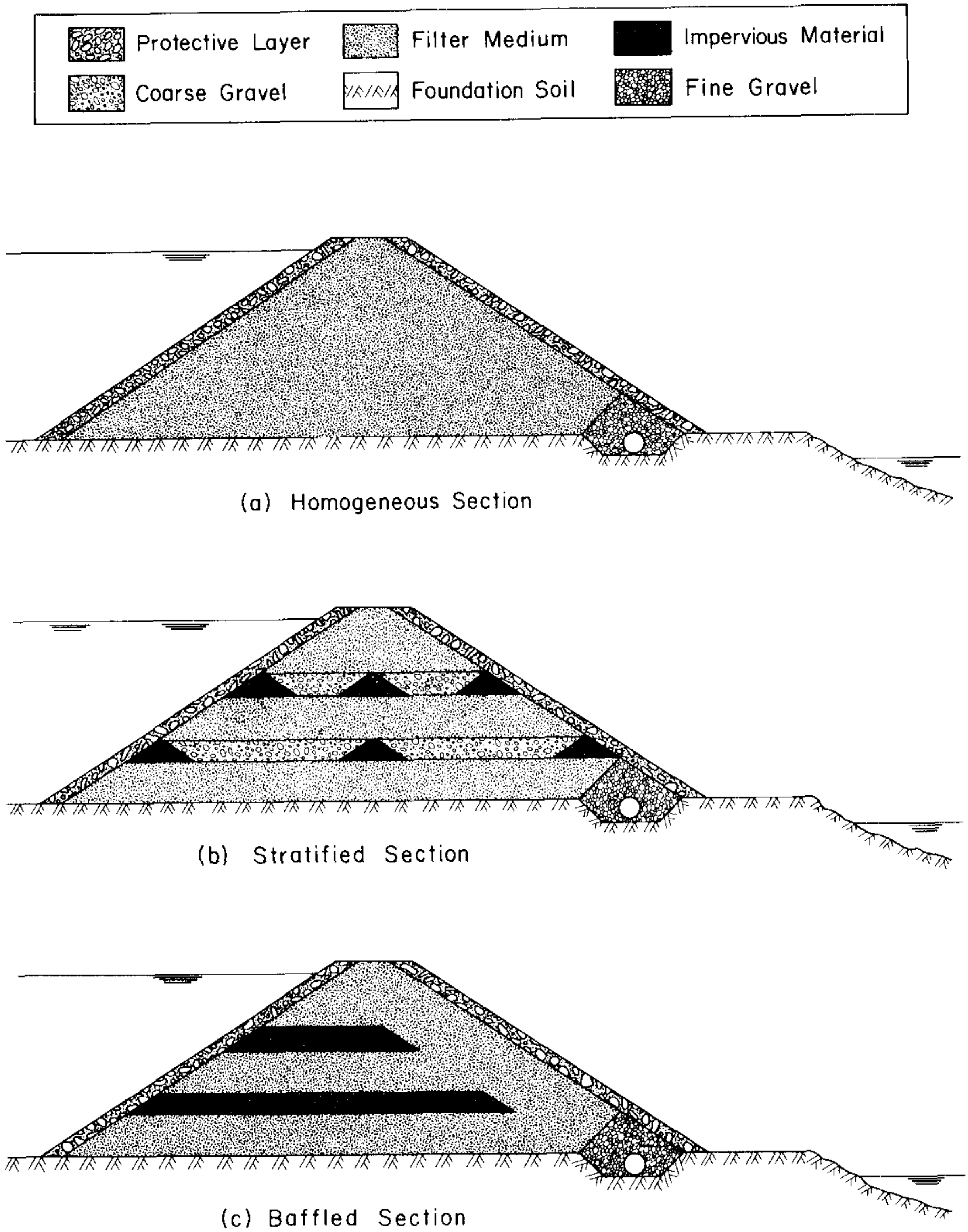

Figure 25. Pervious Dikes

life of the dike and its associated containment facility. Therefore, two alternative solutions are suggested as modifications to the dike shown in Figure 25a.

125. Figure 26 shows a dike whose inside slope is covered with a durable, hard, impermeable material. This arrangement allows the full head to develop while the flow takes place only through a portion of the dike (the lowest portion for the first operating cycle, and incrementally higher portions for subsequent operating cycles). For subsequent operating cycles, the impervious covers can be removed to expose clean layers of filter medium. In Figure 27 an alternative configuration of impermeable covers is suggested. In this case the flow will pass through the entire face of the dike, but only certain portions in the longitudinal direction of the dike will be used during each operating cycle.

126. The design concepts presented in Figures 25b and 25c have the potential to allow different layers of the filter medium to be used at different times, but under such conditions the highest possible hydraulic head can not be used without contaminating all of the filter medium. However, this design could be incorporated with the designs shown in Figures 26 and 27 so that variable level impermeable barriers could be used to maximize the operating head. It can therefore be concluded that modifications such as those presented in Figures 26 and 27 offer the most promising designs for a pervious dike.

127. Filter media. Dikes for disposal areas are seldom built with heights less than 2 to 3 m (6 to 10 ft) and, with appropriate consideration for slope angles and crest widths, filter depths up to 10 or 15 m (33 to 50 ft) can be provided. To achieve a 99-percent removal efficiency with a filter depth of 10 m, a sand with an effective grain size about 1 mm is required (see Figure 19). Sands of this size or larger have exhibited no surface clogging pattern for influents with concentrations of suspended solids less than 1 g/ℓ. Although anthracites with smaller filter depths can provide removal efficiencies equal to those of sands, given the adequately large filter depths available in pervious dikes, it should not be necessary to use the much more expensive anthracites.

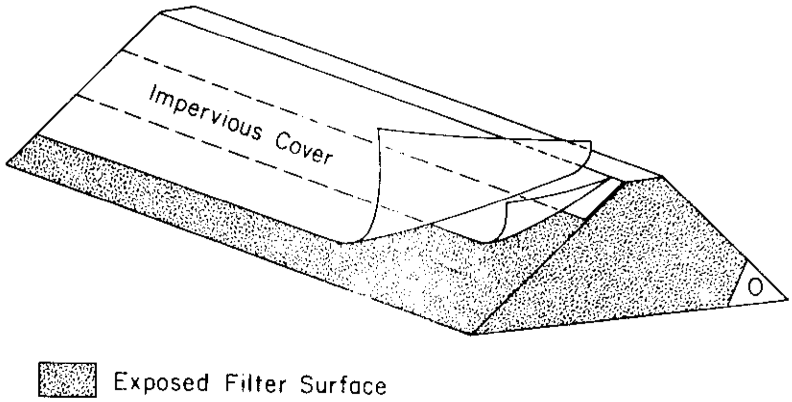

Figure 26. Pervious Dike with Multi-Layered Impervious Cover

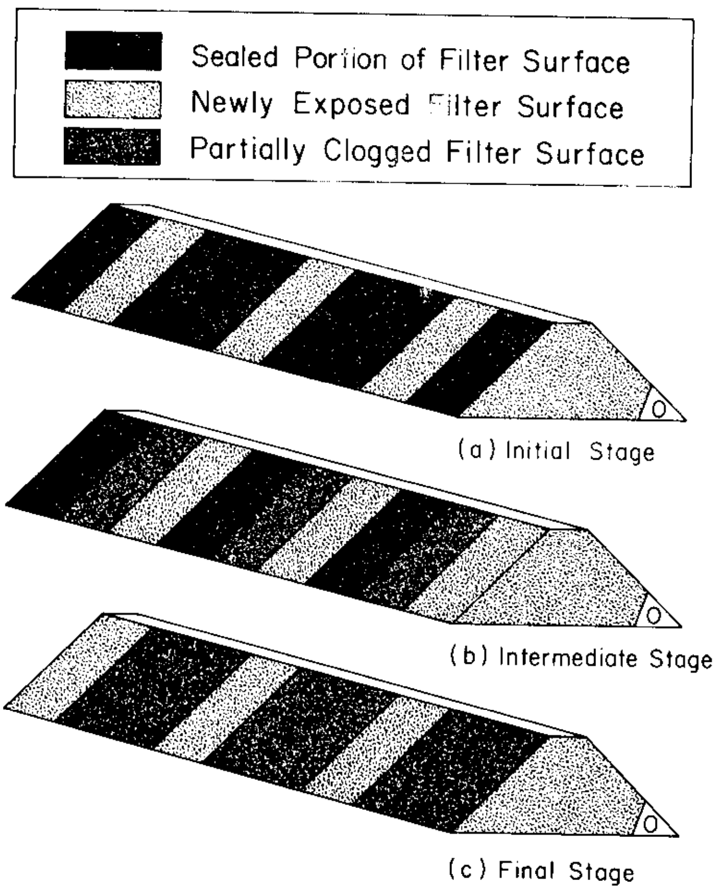

Figure 27. Pervious Dike with Single-Layered Impervious Cover

128. However, the selection of filter media can not be based only on the initial removal efficiency, but it must take into account how this initial efficiency changes with time of operation. With this information it is possible to estimate the expected holding capacity and thus the design life of the filter. It was observed that sands and anthracites with effective grain sizes larger than 2 and 3.5 mm, respectively, do not show clogging tendencies, even for high concentrations of suspended solids (5 to 10 g/ℓ). For experiments with sands and anthracites of smaller sizes, signs of clogging or loss of efficiency were observed when the average specific deposit values became larger than about 0.15 and 0.3, respectively; these specific deposit values are expressed as grams of deposit per gram of filter medium, rather than volume of deposit per volume of bed.

129. Assuming that the in situ density of sands and anthracites is about 120 and 60 pcf (2 and 1 g/cm^3), respectively, the retained solids should not exceed about 0.3 g/cm^3 of filter medium in order for the filter media to function effectively. These values can also be used to estimate the volume of filter medium that is necessary to provide the required efficiency for a specified period of time. An illustration of how these values should be used is included in a subsequent design example of a pervious dike.

Design procedure

130. The design of a pervious dike requires a knowledge of (a) the average and peak flow rates under which it will operate, (b) the estimated concentration of suspended solids approaching the dike, (c) the required effluent quality, (d) the type of dredging operation (intermittent or continuous), and (e) the design life of the disposal area. The steps to be taken in the design are:

- a. Compute the required removal efficiency by comparing the expected influent concentration of suspended solids with the desired effluent concentration.
- b. Estimate an average filter depth by assuming realistic cross-sectional dimensions of the dike.
- c. Use Equation 1 to approximate the filter coefficient of the medium that will provide the required removal efficiency for the estimated average filter length.

d. Determine the effective grain size of the filter medium by means of Equation 3a.

e. Construct appropriate flow nets for the selected type of filter design (see Figures 25, 26, and 27) and compute the discharge per unit length of dike.

f. Calculate the required surface area of the dike and, given the height of the dike, determine the required length of the pervious section.

g. Design the filter to clog within a specified period of time, typically one dredging season for each filter cell; this is accomplished by realizing the maximum specific deposit before the loss in flow rate or effluent quality becomes appreciable.

h. Following the "filter design" (selection of medium and proportioning of the filter), complete the design of the dike by performing appropriate stability analyses.

131. When designing a pervious dike, proper attention must be given to both filter requirements and structural stability. In order to conduct a complete stability analysis for the dike, the flow nets consistent with various design periods should be obtained so that variations in seepage patterns can be properly taken into consideration. For the case of dikes similar to the one shown on Figure 25a, procedures for designing small dams can be adopted with the possible exception of "sudden drawdown" conditions. For dikes with complicated and nonhomogeneous cross-sections, extreme care should be taken when constructing the various flow nets to assure that realistic conclusions are deduced.

Performance capabilities and conditions of operation

132. Pervious dikes should be designed to clarify waters with loads of suspended solids not more than 1 g/ℓ. The maximum hydraulic head should be used, that is, the water level outside the dike should be at or lower than the toe of the structure, and at the inside the water should be able to reach the highest possible level. With the proper selection of filter medium, a pervious dike could be designed to have a removal efficiency of 99 per cent or more. By properly dimensioning the impervious covers, optimum use of the filter media can be achieved.

133. Maintenance. The unique character of this filter system and

the simplicity of its design lead to very low maintenance requirements. However, care must be taken to preserve the integrity of the impervious covers during operation so that they can effectively protect the clean layers of filter medium.

134. Monitoring. The drain of the pervious dike should be equipped with a tube that collects the effluent and transfers it to a common discharge, at which point samples can be monitored for turbidity or suspended solids.

135. Remedial measures. When the quality of the effluent is not acceptable (indicating a nonretaining filter) or when the discharge through the pipe drops too low (indicating a bad clogging condition), parts of the impervious cover can be removed to activate new sections of filter media. Simultaneously, increasing the surface area of the filter reduces the flow rates and improves the filtration efficiency in the areas that may have manifested poorer retention.

Design example

136. Consider the hypothetical case of a disposal area in which (a) the waters approaching the filter system have suspended solids loads of not more than 1 g/ℓ; (b) it is required that effluents do not have more than 20 mg/ℓ suspended solids; (c) the flow rate through the filter is expected to be about 0.15 m^3/sec; and (d) the dike is 3 m high with a crest width of 1.5 m and slopes of 2 horizontal on 1 vertical. According to the estimated influent and required effluent concentration of suspended solids, a removal efficiency of 98 per cent should be achieved For the given cross-sectional dimensions of the dike, the average filter depth (according to flow line lengths) will be about 10 m. From Equation 1 the required filter coefficient is found to be about 0.39 m^{-1}; and from Equation 3a or Figure 19 it is determined that a sand with an effective grain size of 1 mm can provide the required efficiency.

137. Next, a type of design is selected according to the configuration of the impervious cover that is most appropriate. Then, a simple flow net should be constructed to obtain the shape factor (ratio of number of flow tubes to number of potential drops in a conventional flow net with "squares") for the seepage domain. If the shape factor is

assumed equal to 0.2, use of a filter medium with a permeability of 0.5 cm/sec would lead to a required filter surface of about 300 m^2.

138. The permeability of the filter medium can be determined by use of Hazen's formula, $k(\text{cm/sec}) = C\, D_{10}^{\;2}$, where D_{10} is the effective grain size in cm and C varies from 80 to 140 with the higher values tending to be associated with higher angularity of the grains. This relationship, however, has been developed for clean filter sands, and minute quantities of silt or clay can diminish the permeability considerably. To predict the permeability of media with grains having high angularity (such as anthracites), Kozeny's equation with appropriate coefficients or Hazen's equation with high values for C can be applied.

139. Finally, the ability of this area of the dike to retain the necessary amounts of solids before clogging must be checked. Assuming a dredging season of two months, the total throughput per unit area will be approximately 250 ℓ/cm^2; since the amount of solids retained is about 1 g/ℓ (desired removal efficiency is 98 per cent), the total loading of solids per unit surface area of filter will be about 250 g/cm^2. Given that the filter depth is about 10 m (or 1000 cm) and assuming a uniform distribution of deposit with depth (laboratory studies reported in Part IV support this assumption), about 0.25 grams of solids will be retained by each cubic centimeter of filter media. Since this is less than the value of 0.3 g/cm^3, which is considered to be the maximum attainable deposit before clogging, the design surface area is adequate.

140. For this design example, it was assumed that the flow rate through the filter (and, consequently, the flow rate through the disposal area) was about 0.15 m^3/sec. Such flow rates correspond to continuous dredging with an 8 to 9 inch pipeline dredge or to intermittent operations with larger pipeline dredges or with hopper dredges. For the case of continuous operations with a much larger dredge (say, a 24 inch pipeline dredge), the flow rate would be much higher (1 to 2 m^3/sec). Consideration of such flow rates would have resulted in filter areas about an order of magnitude larger than those estimated. The cost of constructing such a facility would be large and might render this filtration alternative economically unfeasible.

Discussion

141. The foregoing example was selected to represent the conditions associated with a typical disposal area (flow rate, size of dike, and active life per year), and it leads to the following observations:

- a. For concentrations of suspended solids on the order of 1 g/ℓ, extremely large sections of pervious dike are required.
- b. When the load of suspended solids is on the order of 1 g/ℓ and the required removal efficiencies are very high (95 per cent or more), the pervious dikes will tend to clog rapidly.
- c. Pervious dikes appear to be most useful when a low removal efficiency is required, or when the suspended solids load of the influent is not more than a few tenths of a gram per liter, or when the active dredging period is short, or when low flow rates are expected.

Sandfill Weirs

142. Conceptually, a sandfill weir may overcome some of the disadvantages and limitations of a pervious dike. This type of filter system consists of one or more cylindrical or rectangular cells that contain the filter medium and provide filtration in a vertical direction of flow.

Filter design concepts

143. Compared to a pervious dike, a sandfill weir offers the following advantages:

- a. Corrective measures can be applied much more easily to restore effluent quality or quantity.
- b. Components can be removed from operation periodically for cleaning and other maintenance.
- c. The system is more readily adaptable to disposal areas that are being continuously rejuvenated (that is, used as transfer stations).
- d. Operation under a high hydraulic head is possible (hydraulic gradients on the order of unity can be realized in downflow modes).
- e. Construction may incorporate a vertical face, and this may offer an advantage if the facility is built in a limited space.

f. Standby units can be provided for use in emergency situations (for example, if there is an abrupt change in influent quality or volume of influent).

However, sandfill weirs have also limitations, the most important of which are:

a. Filter depths are essentially limited by the level of water inside and outside the disposal area.

b. Their use for influents with high concentrations of suspended solids (on the order of several grams per liter) requires excessive maintenance and large excess capacity.

144. Alternative designs. Sandfill weirs can be designed to operate in a downflow or in an upflow mode, as illustrated in Figures 28a and 28b. The available hydraulic head is the primary factor that dictates which of the two systems should be used. High hydraulic head results in high flow rates, and this reduces the required surface area of the filter; therefore, for cases where the water level outside the filter cells is relatively low (as shown in Figure 28a), a downflow design is probably preferable. When high hydraulic heads can not be achieved, the upflow design is generally more desirable because the limited data available indicate that upflow filters can sustain longer runs and show better removal efficiency than downflow filters under the same hydraulic head. The buffer wall shown in Figure 28b allows the maximum head to develop before the weir starts to function, and it provides filter influents with the lowest possible concentration of suspended solids.

145. Filter media. The filter depths that can be realized and the removal efficiencies that must be satisfied dictate the type of filter media that should be incorporated in sandfill weirs. Although either sands or anthracites of various effective grain sizes can be used, effective grain sizes larger than 1 and 2 mm for sands and anthracites, respectively, should be avoided because excessive filter depths would be required to achieve high removal efficiencies (90 per cent or more). Since these filter media have been shown to clog relatively fast under high concentrations of suspended solids (5 to 10 g/ℓ), the use of sandfill weirs is limited to the treatment of influents with concentrations of suspended solids less than 1 or 2 g/ℓ. Depending on the required

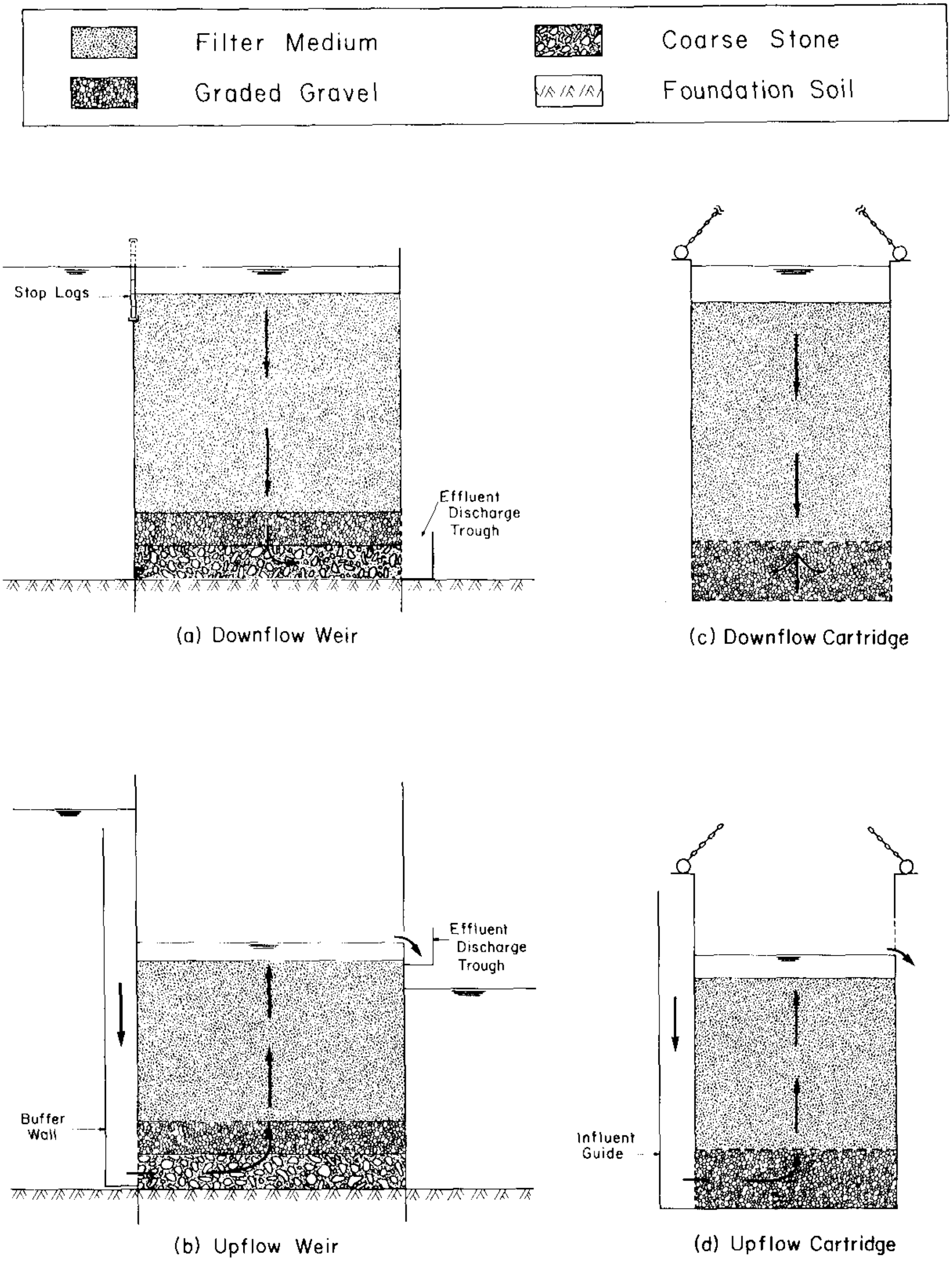

Figure 28. Downflow and Upflow Weirs and Cartridges

removal efficiency and the available depth, specific media can be selected by use of Equations 1, 3a, and 3b. However, it should be realized that anthracites require a significantly smaller filter depth to provide the same removal efficiency as sands of equal grain size; alternatively, for the same filter depth, a coarser anthracite can be used to achieve a higher flow rate. As specified for pervious dikes, the retained solids should not exceed 0.3 g/cm^3 of filter medium in order for the system to function effectively.

Design procedure

146. A disposal area should be equipped with a battery of sandfill weirs, rather than a single weir, to allow for continuous operation, because a period of one to two days may be required to empty and refill a filter cell. The proper design of a battery of sandfill weirs requires a knowledge of (a) the average flow rate that must be accommodated, (b) the available hydraulic head, (c) the estimated loads of suspended solids in the influent, and (d) the required effluent quality. The steps to be taken in the actual design are:

a. Depending on the available hydraulic head, select the type of filter (downflow or upflow) and determine the maximum filter depth that can be utilized.

b. Compute the required removal efficiency by comparing the loads of suspended solids expected in the influent and desired in the effluent.

c. Use Equation 1 to estimate the filter coefficient of the medium that will provide the required removal efficiency for the maximum available depth.

d. Use either Equation 3a or 3b to estimate the effective grain size of the sand or anthracite that can be used.

e. With a knowledge of the available hydraulic head and the filter depth, estimate the permeability of the medium and use Darcy's Law to determine the required surface area of the filter.

f. Select the diameter of each cell and determine the number of cells required.

g. Increase the required number of cells by one or two to allow for idle time.

h. Determine the effective lifetime of the selected filter media, and estimate how often the weirs will have to be cleaned.

Performance capabilities

147. Sandfill weirs will probably be rather ineffective if the concentrations of suspended solids in the influent exceeds 1 or 2 g/ℓ. However, within the indicated range of solids loading and depending on the filter medium and the filter depth, removal efficiencies of up to 99 percent or more can be achieved. However, it is recommended that suspended solids loads higher than 1 g/ℓ be avoided and that the maximum available filter depths be used.

148. Operation and maintenance. Before the weirs are activated, the disposal area should be filled to the maximum allowable water level. This procedure will provide the highest hydraulic gradient, and it will allow the longest retention time for the supernatants within the containment area. Flow into the weirs can be controlled with properly designed stop-logs (see Figure 28a). When a filter cell has lost its filtration efficiency or has clogged (judged from monitoring cell effluents), it should be removed from operation, emptied, and refilled with clean filter medium. The contaminated filter media can be either washed at a nearby facility (the washwaters may be returned to a special compartment of the disposal area) or deposited inside the disposal area.

149. Monitoring. The effluent of each filter cell can be collected in a trough (see Figures 28a and 28b) that has a single overflow point (perhaps a weir) at which the discharge can be monitored and samples can be taken to determine the effluent quality.

150. Remedial measures. The design of a sandfill weir is relatively flexible, and remedial measures can easily be taken. During cleaning cycles, the type of filter medium can be changed to improve effluent quality or flow rates. When a cell is not performing according to specified design standards, it can easily be taken out of operation.

Design example

151. As an illustrative example, consider the case of a disposal area in which (a) the influent to the filter system has about 1 g/ℓ of suspended solids, (b) the effluent quality is required to be 1.5 times that of the ambient waters, (c) the flow rate through the filter is expected to be about 0.15 m^3/sec, and (d) the maximum available hydraulic

head is 2 m. Assuming that the ambient waters have about 10 mg/ℓ of suspended solids, the removal efficiency of the filter should be 98.5 percent. Assume further that a downflow filter will be employed, and the filter depth is not expected to be larger than 1.5 m. From Equation 1 the required filter coefficient is found to be 2.8, which, according to Equations 3a and 3b, corresponds to a sand or an anthracite with an effective grain size of 0.35 and 0.75 mm, respectively. It was shown in Part IV that a sand with this grain size would clog in a matter of hours under an influent with 1 g/ℓ of suspended solids. Therefore, if a downflow filter is desired, the anthracite should be used.

152. Assuming that the permeability of the anthracite can be approximated by Hazen's formula, a value of 0.6 cm/sec can be determined. Assuming further a hydraulic gradient of unity, the required surface area for the filter is found to be about 25 m^2. For cells that have a diameter of 3 meters, the minimum number required is four; however, at least one and preferably two additional cells should be constructed to account for idle time. A similar scheme of computations can be followed to design an upflow sandfill weir system.

153. Finally, an estimate should be made of the time required for the filter media to clog. Since the total volume of the filter medium is 37.5 m^3, it should be able to retain about 11,250 g of solids before showing signs of severe clogging. The flow of 0.15 m^3/sec corresponds to a required removal of about 150 g per second. Assuming a uniform distribution of deposit, the time to reach the indicated clogging point would be about 21 hours; hence, a daily replacement of the filter media would be required. If the solids load to the sandfill weir were reduced by a factor of 10, the media would need be changed only once every 10 days.

154. As explained for pervious dikes, flow rates larger than those assumed in this example would have resulted in larger required filter surface areas. Since the required areas are proportional to the flow rates, the use of weirs may be unrealistic for high flow rates (on the order of 1 m^3/sec). For example, the required surface area for a 27 inch dredge (flow rate of 1.35 m^3/sec) would be about 225 m^2 (32 cells). However, these requirements could be reduced by providing larger filter depths.

If the filter depth were 3 m, the required effective grain size of the anthracite would be 1.1 mm (Equations 1 and 3b), and the permeability of the medium would be about 1.2 cm/sec (according to Hazen's formula); hence, the required area would be 112.5 m^2, or one-half of the area estimated above.

Discussion

155. The foregoing information and the design example lead to the following observations:

- a. Sandfill weirs will require extensive maintenance if they are used to clarify influents with suspended solids loads greater than 1 g/ℓ and provide high removal efficiencies.
- b. The amount of idle time can be reduced considerably if low removal efficiencies are required, or if the influent has a low concentration of suspended solids, or if the flow rates are low, or if the active dredging period is short.

Granular Media Cartridges

156. Similar to the concept of sandfill weirs, but much smaller in size, granular media cartridges provide maximum flexibility in the combination of types of filter media, flow direction, depth of filter, and hydraulic head. However, maintenance and operational requirements, as well as costs, may become excessive.

Filter design concepts

157. Granular media cartridges have the following characteristics and advantages:

- a. Because of their relatively small size and weight, they can be handled by a small crane.
- b. Once spent and requiring rejuvenation, they can be replaced in a matter of minutes.
- c. They can be used advantageously in disposal areas that are continuously rejuvenated. As conditions change in the disposal operation, cartridges of alternate media could be supplied and operating personnel could experiment to obtain the best performance.
- d. Corrective measures can be easily taken.
- e. Filter depth can be controlled by stacking cartridges on top of each other, if appropriately designed.

f. High hydraulic heads can be used, but cartridges can also be used where only low hydraulic heads are available.

158. Financial considerations may limit the use of cartridges for the case of influents with very high suspended solids loads (on the order of several grams per liter). In such a case cartridges would have to be replaced frequently, and the soiled media would have to be washed or wasted.

159. Alternative designs. The diameter of each cartridge should not exceed 1 to 1.5 m, and the depth should be limited to not more than 2 to 2.5 m. Larger cells would weigh several tons and would be too heavy to be handled easily by a small crane. As shown in Figures 28c and 28d, cartridges can be designed to operate in downflow or upflow modes. Shown in Figures 29a and 29b are combinations of filter cells that result in biflow modes of operation. Such configurations can use downflow and upflow cartridges or perhaps weirs. The configuration shown in Figure 29c (horizontal flow) does not appear to offer the technical advantages that are realized with the biflow concept and it is not recommended. Figure 30 gives plan and elevation views of a typical cartridge installation. The merits and limitations of upflow and downflow modes for cartridge operation are essentially the same as those discussed in the section on sandfill weirs.

160. Filter media. The type and gradation of filter media that are usable in cartridges is limited by the filter depths that can be utilized. For the selection of a filter medium, Equations 1, 3a, and 3b can be used as described in the sections on pervious dikes and sandfill weirs.

Design procedure

161. The design of a battery of cartridges requires a knowledge of (a) the average flow rate that must be accommodated, (b) the available hydraulic head, (c) the estimated load of suspended solids in the influents, and (d) the required effluent quality. The steps to be taken in the design are:

a. Select the type of flow consistent with the available hydraulic head.

b. Compute the required removal efficiency.

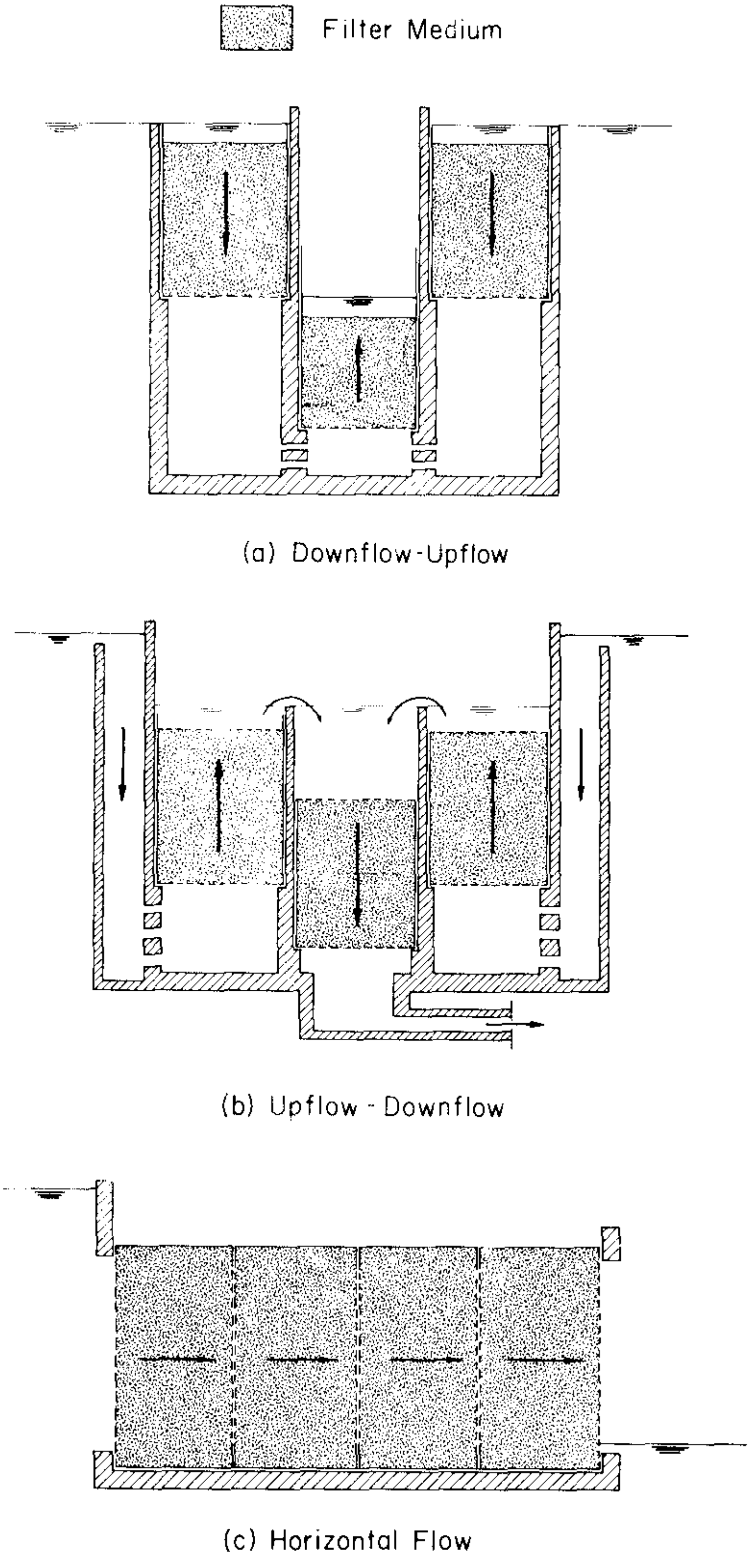

Figure 29. Biflow Mode of Operation for Cartridges and Sandfill Weirs

c. Use Equations 1, 3a, and 3b to select the filter medium (sand or anthracite) and effective grain size.

d. Determine the required surface area by use of Darcy's Law, the available hydraulic head, the cartridge depth, and an estimate of the medium permeability.

e. Select the diameter of a typical cell and determine the number of cells.

f. If desirable, provide for extra cells; however, this may not be necessary because the substitution of cells can be done rapidly.

Performance capabilities

162. Cartridges can be used to clarify waters with suspended solids loads that can be as low as several hundred milligrams per liter or as high as a few grams per liter. Different filter media can provide any required removal efficiency up to 99.9 per cent. However, for loads of suspended solids on the order of 5 to 10 g/ℓ, intensive maintenance will be required, because the cartridges are not expected to have an effective life time longer than a day. A system of downflow and upflow cartridges in series can provide excellent removal efficiencies and also increase the filter depth that can be used.

163. Operation and maintenance. Before the batteries of cartridges are activated, the water in the disposal area should be allowed to reach its maximum level. Flow into the batteries of cartridges is controlled by stop-logs in a manner similar to that shown in Figure 30. When a cartridge has lost its effectiveness, removal and replacement is relatively easy. Contaminated filter media can be either wasted or washed and reused.

164. Monitoring. As for sandfill weirs, each battery of cartridges can be easily monitored by measuring flow rates and water quality in a discharge trough (Figure 30).

165. Remedial measures. Steps similar to those described for a sandfill weir can be taken to correct any malfunction. Basically, however, cartridges facilitate a more flexible design, because any maintenance, restoration, or alteration of efficiency can be achieved in a much shorter period of time.

Design example

166. Consider the hypothetical case of a disposal area where (a) the

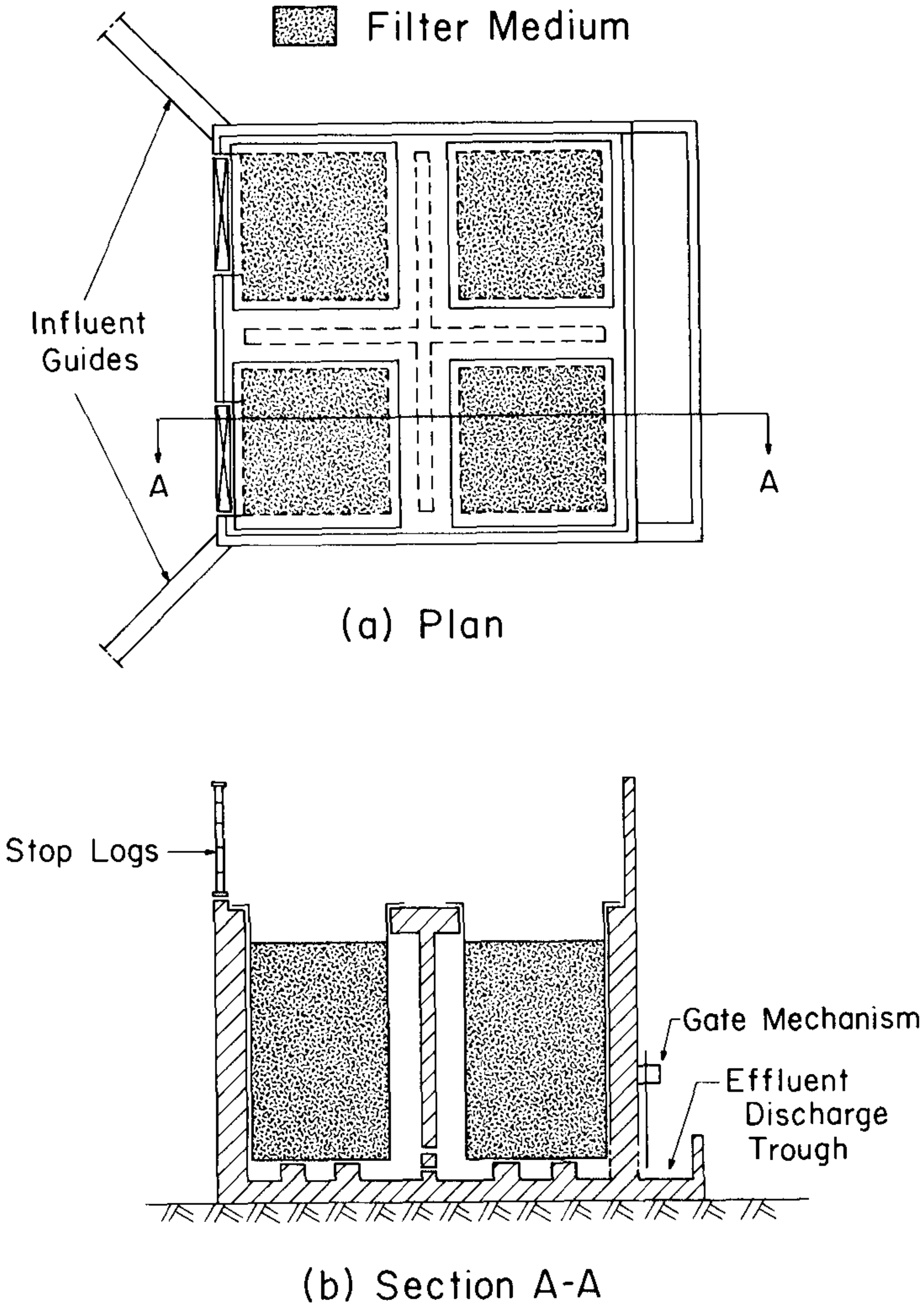

Figure 30. Typical Arrangement of Cartridge Battery

influents to the filter system have about 2 g/ℓ of suspended solids; (b) the required effluent quality is 50 JTU above ambient turbidity; (c) the flow rate through the filter system is expected to be 0.15 m^3/sec; and (d) the available head difference is about 3 m. For the specified effluent standard, waters with about 100 mg/ℓ of suspended solids would probably be acceptable. Therefore, the system should have a removal efficiency of approximately 95 per cent.

167. If cartridge depths of 2 m are selected, the effective filter depth, accounting for inlet and outlet zones, will be at least 1.5 m. The required filter coefficient is found from Equation 1 to be 2.0 and from Equations 3a and 3b the effective grain sizes of the sand and anthracite that will give the required efficiency will be about 0.42 and 0.90 mm, respectively. For the case of sand, the required surface area is found to be 85 m^2, but for anthracite only 18.5 m^2 are needed. The required number of cartridges with a diameter of 1 m is 108 in the case of sand-filled cartridges or 24 in the case of anthracite-filled cartridges. Anthracite appears to be the choice in this case because it will reduce the size of the installation, as well as the number of active cartridges, by about a factor of 4. Because anthracite weighs only about one-half as much as sand, much larger cartridges of anthracite can be used; thus, only 6 cartridges with a diameter of 2 m would be required. For the same problem, if a higher removal efficiency was required a combination of downflow-upflow cartridges could be used. As for the cases of pervious dikes and weirs, it is likely that an unrealistic number of cartridges would be required for flow rates much higher than those used in the example.

Mechanized Sandfill Weirs

168. It is apparent from the foregoing discussions that nonmechanized filter systems, especially the sandfill weirs, will present a considerable maintenance problem when the concentration of suspended solids in the influent is on the order of 1 g/ℓ. A modification of the sandfill weir that includes backwashing facilities to quickly clean the filter bed

is shown in Figure 31. The design of the filter cells with respect to the type of filter medium, the depth of filter, and the filter surface area is similar to that described for the nonmechanized sandfill weirs. As shown in Figure 31, the following auxiliary equipment is necessary:

- a. A pump to feed the influent to the filter in the case of a low water level inside the disposal area.
- b. A pump to divert the filtrate into the backwash storage tank.
- c. Valves to control the flow of water during filtration and backwashing cycles.
- d. A channel to return backwash waters to the disposal area.

169. The advantages offered by this system are:

- a. Cleaning of the cells in-place by removing the filter medium is avoided.
- b. Concentrations of suspended solids up to 1 or 2 g/ℓ can be handled.
- c. One person can easily oversee and monitor the installation.

170. With regard to the flow rate and frequency of backwashing, guidelines similar to those used for conventional deep-bed filters can be adopted. For such systems, many designers limit the maximum volume of the backwash waters to 5 per cent of the total throughput. Furthermore, data presented herein indicate that the media should be backwashed when the specific deposit reaches about 0.3 g/cm^3. Considering the foregoing design example for sandfill weirs, it is seen that the weirs will require cleaning every 2[illegible] hours. Since the total throughput for this period is about 11,000 m^3 (3 million gallons), 5 per cent of which is 550 m^3 (150,000 gallons), a backwashing duration of 5 minutes with a flow rate of 1.3 to 2.0 cm/sec (20 to 30 gpm/ft^2) will require about 100 m^3 (25,000 gallons) of backwash water, and this amount can easily be pumped and stored in a small size tank.

Summary

171. On the basis of an extensive experimental investigation reported in Parts III and IV, three new conceptual designs are proposed for

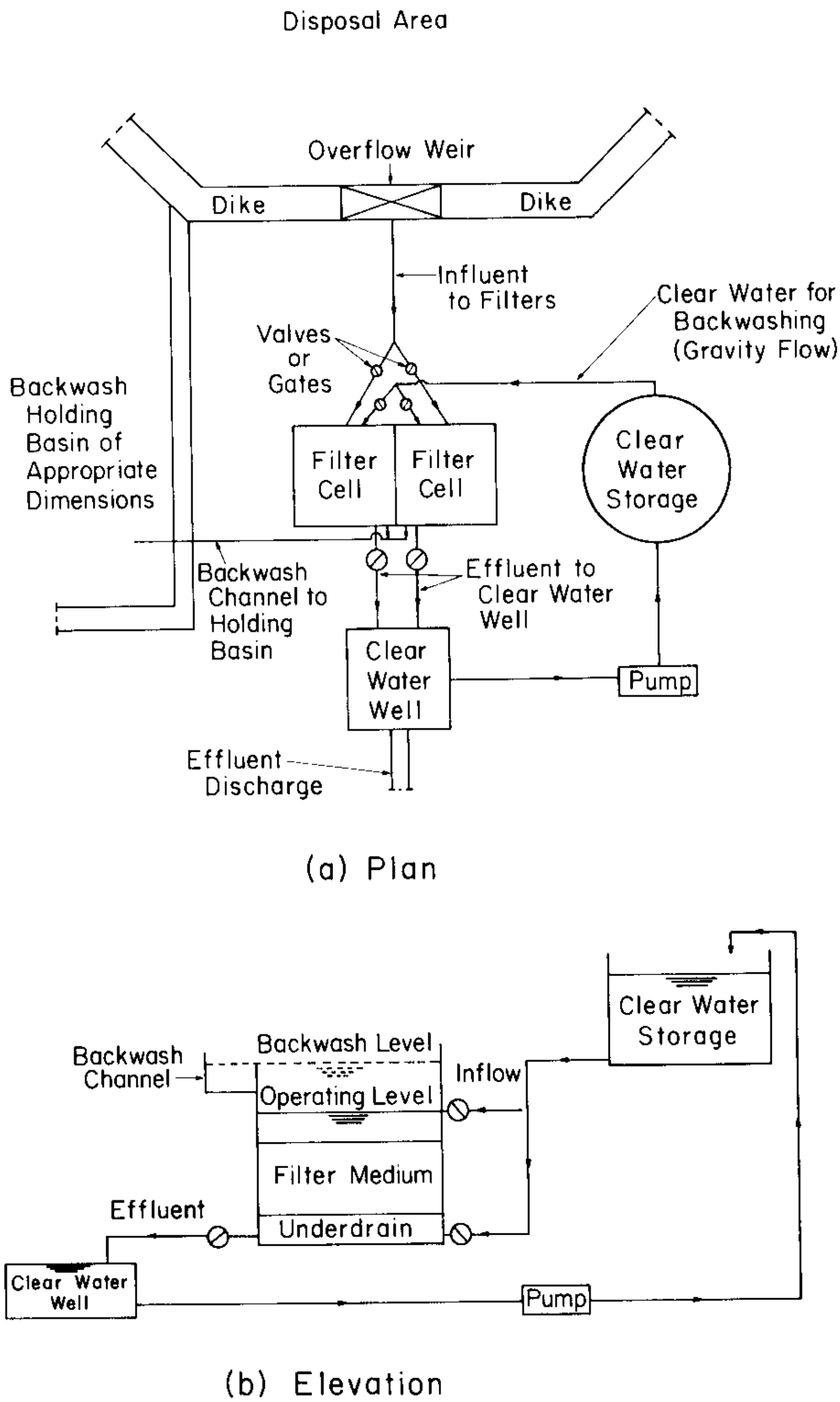

Figure 31. Typical Mechanized Sandfill Weir

nonmechanized granular media filter systems. Pervious dikes, sandfill weirs with or without backwash, and granular media cartridges comprise a special group of systems that have the following characteristics: (a) they use the maximum head of water that can be developed inside a disposal area; (b) they effectively clarify waters with concentrations of suspended solids up to 1 g/ℓ (pervious dikes and weirs with or without backwash) or up to 10 g/ℓ (weirs with backwash and cartridges); (c) they are simple in design, operation, and monitoring; (d) their properties can be adjusted to control effluent quality (except for pervious dikes); and (e) maintenance and manpower requirements are negligible for dikes, low to moderate for weirs, and moderate to high for cartridges. On the basis of their technical feasibility, these three systems are strong candidates for use in the clarification of supernatants from dredged material disposal areas. However, for dredging operations in which high flow rates (about 1 m^3/sec) are obtained continuously, the required size of these systems may render them economically unfeasible.

172. Many factors affect the selection and application of conventional or conceptually new solid-liquid separation technology to the design of efficient dredged material confinement facilities; these factors include the size and location of the disposal area, the type of influent slurry, and the effluent quality standards. However, these factors may vary considerably with local conditions, and a large number of combinations may result. Accordingly, there is a need to establish design guidelines that have general applicability and a sufficiently good predictive capability for a wide variety of situations.

173. The following sections of this chapter describe the various design guidelines that have been developed, and several simple nomographs are presented to assist the designer in (a) determining the gradation and concentration of suspended solids in disposal area effluents, (b) selecting the proper material to be used in a granular filter medium design, and (c) estimating the effective cycle time or life-time of a granular media filter. The types of solid-liquid separation technology that are applicable to the design of dredged material disposal areas include sedimentation, chemical coagulation and flocculation, vacuum filtration, sonic screening, and granular media filtration by means of conventional equipment with automatic backwashing, and granular media cartridges. These systems were incorporated in the preparation of design flow charts that consider all possible alternative means to effect a given degree of solid-liquid separation.

Operating Conditions of Disposal Areas

174. The introduction of new or alternative solid-liquid separation technology to the design of confined disposal areas for dredged material requires a thorough understanding of the prevailing operating conditions of these disposal areas. The consideration of extreme, as well as intermediate, conditions is necessary so that the problem can be properly put into perspective. Operating conditions can be adequately described by

considering the geometry of the disposal area, the type of slurry discharged into the area, and the effluent quality standard that must be satisfied. In the following paragraphs, these factors are discussed and the necessary ranges of values are selected to describe operating conditions adequately.

Disposal area geometry

175. The sizes of dredged material confinement facilities are dictated by the volume of bottom sediments to be dredged, the frequency of dredging operations, and the available tracts of land. All disposal areas, irrespective of their size, function as a gross sedimentation basin in which dredged material is deposited hydraulically. Therefore, the principal characteristic of a disposal facility is the size of the area that is inundated continuously and serves as the sedimentation basin. Since the size of this inundated area may be rather large for long-term permanent containment facilities or relatively small for short-term temporary storage facilities, such as transfer stations, design relationships and considerations are developed to cover surface areas ranging from 10,000 m^2 to 1,000,000 m^2 (2.5 acres to 250 acres).

Influent to disposal areas

176. To characterize the dredged material slurries that are pumped into disposal areas, three parameters are necessary: the rate of influent pumping, the amount of suspended solids in the slurry, and the grain size distribution of the suspended solids. Once a disposal area is filled with water after the initiation of a dredging season, the volume of slurry pumped into the area can be equated to the volume of water being discharged from the disposal area. Although the discharge rate is usually a few tenths of a cubic meter per second, a range of 0.01 m^3/sec to 1 m^3/sec is selected in this conceptual development. Dredged material slurries, as pumped into disposal areas, usually contain between 10 and 20 percent suspended solids by weight; therefore, the chosen range of 5 to 25 percent is considered to encompass virtually all conditions that would likely be encountered. As shown in Part II and Appendix A, the gradations of bottom sediments that are candidates for dredging vary significantly, both regionally and locally. It was further

established in Part II that gradations obtained according to standard ASTM procedures (which involve the use of a dispersing agent when conducting the hydrometer test) overestimate the percentage of colloidal fines in the bottom sediments by at least a factor of two. Finally, it is assumed herein that the mass percentages of grains finer than 10, 1, and 0.1 μ are not more than 50, 20, and 0 percent, respectively.

Effluents from disposal areas

177. In the past, the quality of effluents from disposal areas was judged to a large extent by their concentration of suspended solids. Effluent quality standards, in turn, dictated the suspended solids retention efficiency that should be satisfied by a dredged material confinement facility. Past standards have not been uniform, as summarized in Part II, and they ranged from extremely strict to very lenient. Specifically, accepted suspended solids content of effluents ranged from as high as 13 g/ℓ to as low as a few tens of milligrams per liter.

178. New interim guidelines were recently imposed (see Part II) to govern the discharge of dredged or fill material into navigable waters, but specific instructions for evaluation of the quality of such discharges are not yet available. Therefore, effluent quality standards were assumed herein to specify suspended solids contents in the range of 10 mg/ℓ to 13 g/ℓ.

Sedimentation Analysis

179. Sedimentation in a disposal area is a natural solid-liquid separation process that incurs virtually no operational or maintenance expenses and, except for the initial investment for land acquisition and dike construction, involves no capital cost. In order to design a filter system to supplement the solid-liquid separation by sedimentation and thus clarify further disposal area effluents, an estimate of the amount and type of suspended solids to be encountered by the filter system is required. Therefore, the designer should be provided with a method by which the concentration and sizes of suspended solids in disposal area effluents can be estimated.

180. In Appendix D classical sedimentation basin theories are presented and adapted to the operating conditions of dredged material disposal areas. When the discharge and surface area of a disposal facility are known, the percentage of particles of various sizes that are removed from suspension by sedimentation can be computed from Equation D5. The ratio of discharge to surface area is called the surface loading; it is expressed in centimeters per second and, according to values selected in the foregoing paragraphs, ranges from about 10^{-6} to 10^{-2} cm/sec. Suspended particle removal efficiencies predicted by Equation D5 for different size particles are plotted in Figure 32a versus a wide range of surface loadings. In Figure 32b the removal efficiencies are cross-plotted against the suspended particle size for various surface loadings. Depending on the size of the disposal area and the flow rate through it, Figure 32b can be used to estimate the amount of suspended particles of a given size that will settle out of suspension in the disposal area. For example, for a surface loading of 10^{-5} cm/sec, all particles larger than 5μ are expected to settle, and about 90 percent of the 1-μ particles will be removed.

181. To expedite the determination of the concentration of suspended solids in disposal area effluents, the nomograph presented in Figure 33 was developed on the basis of the assumptions that (a) Equation D5 predicts with reasonable accuracy the amount of particles of a certain size that will be retained by a disposal area with a given surface loading value; (b) the mass of particles with equivalent diameters smaller than 0.1μ is negligible; (c) the masses of particles smaller than 1μ and 10μ are not more than 20 and 50 per cent by weight, respectively; (d) all particles larger than 10μ will be removed by sedimentation; and (e) the distribution by weight of particles smaller than 10μ is uniform. Based on the second and third assumptions, the ten gradation curves shown in Figure 33 were selected to cover the range of gradations expected in dredged bottom sediments. Assumption (e) was made in order to provide a standard basis for performing the computations necessary to develop the nomograph. The use of the nomograph is explained as follows:

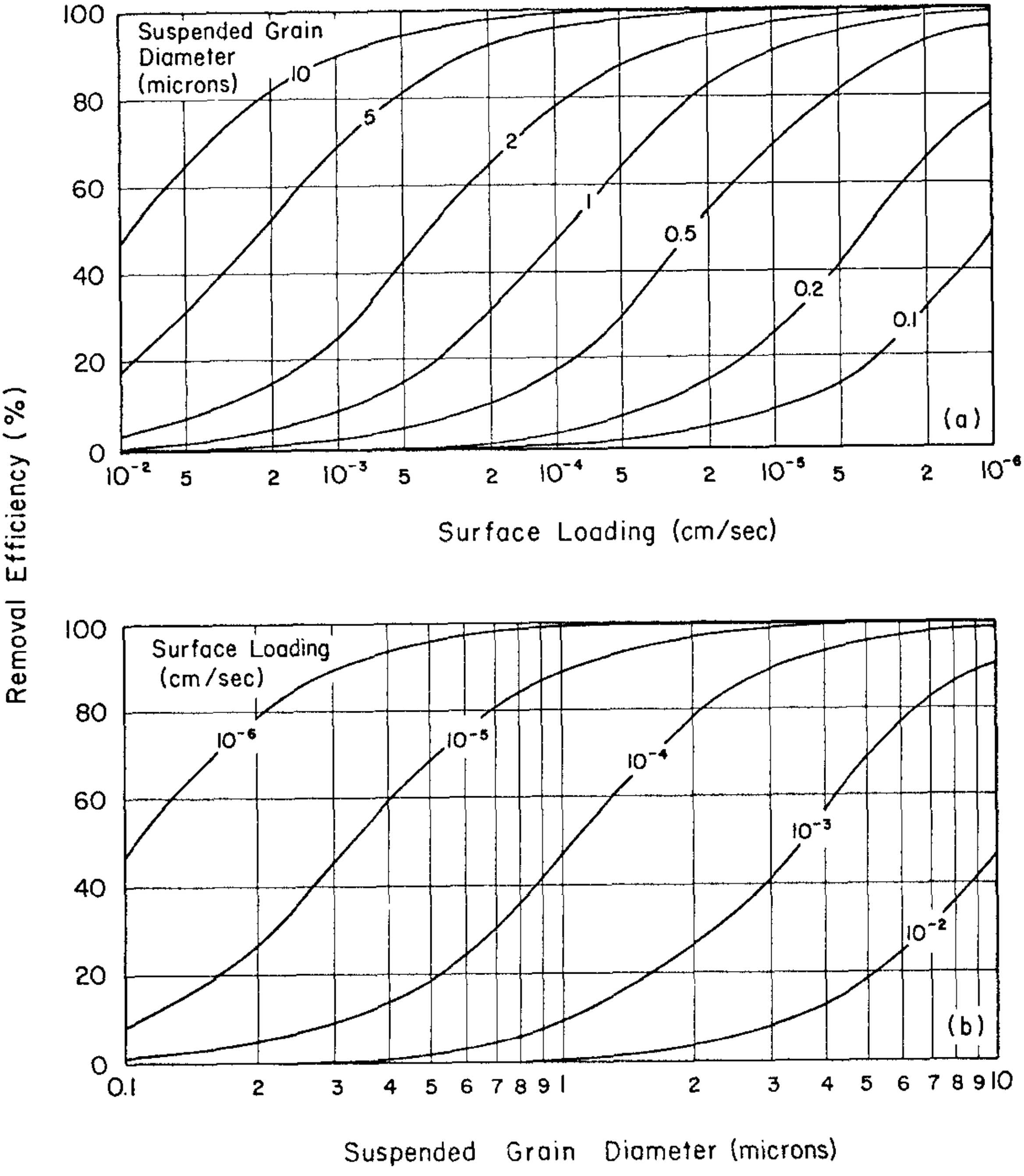

Figure 32. Relationships Among Removal Efficiency by Sedimentation, Surface Loading, and Suspended Grain Size

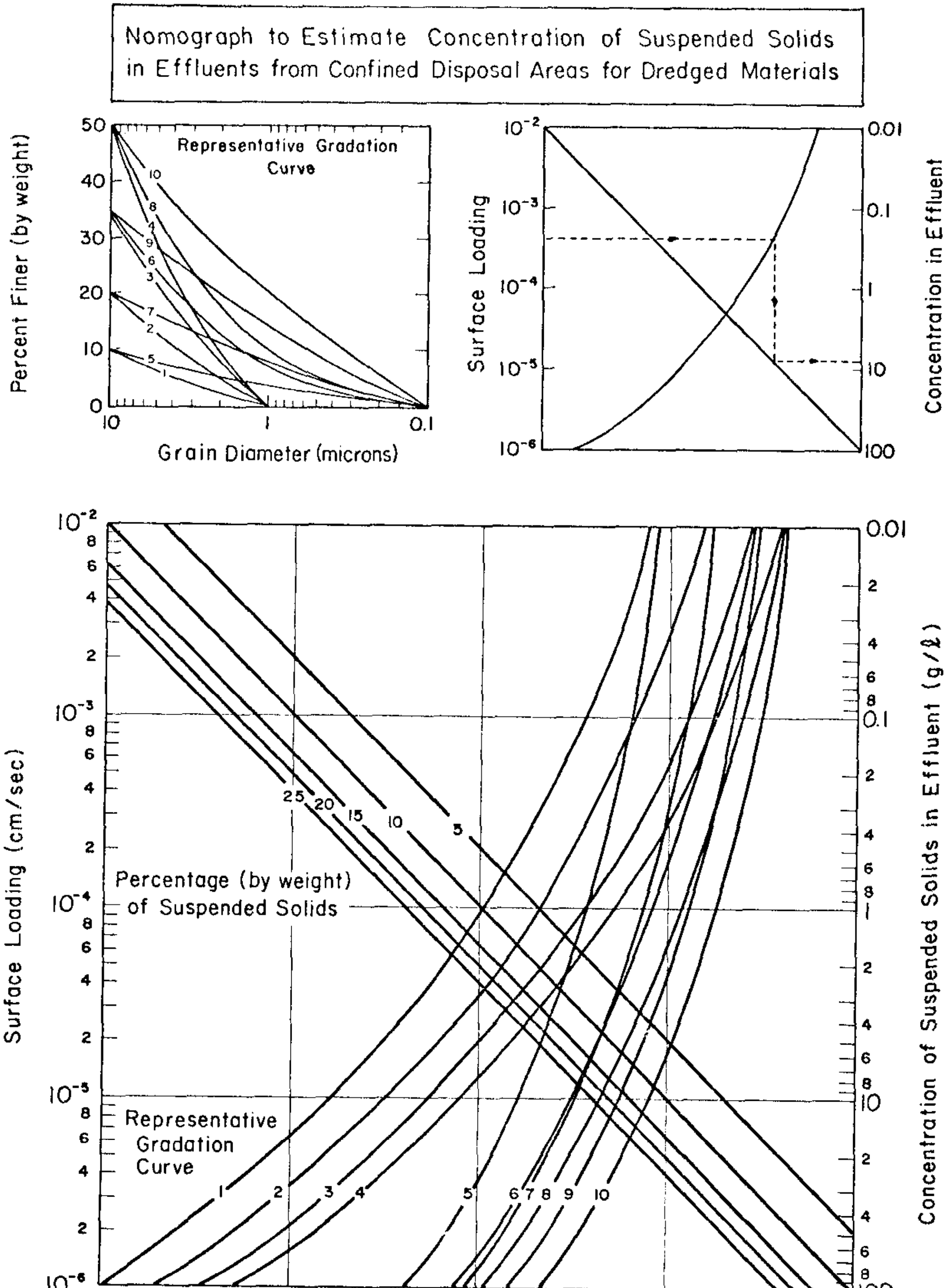

Figure 33. Relationships Among Surface Loading, Amount and Gradation of Suspended Solids in Dredged Material Slurry, and Concentration of Suspended Solids in Effluent

a. Determine the value of the surface loading from a knowledge of the disposal area size and its expected flow rate.

b. Identify the grain-size distribution curve of the bottom sediments to be dredged and select from Figure 33 the representative gradation curve that gives the best fit. If hydrometer tests are employed to obtain the distribution curve, they should be performed without the use of a dispersing agent.

c. Estimate the suspended solids content of the slurry to be pumped into the disposal area.

d. Enter the nomograph from the left and move to the right until the selected representative gradation curve is encountered. Move up or down until the appropriate line representing the percentage of suspended solids in the slurry is met. Exit the right side of the nomograph and read the concentration of suspended solids in the effluent.

182. For example, for a surface loading of 10^{-5} cm/sec, a grain-size distribution represented by curve 4 of Figure 33, and a slurry concentration of 10 percent suspended solids by weight, the effluents should be expected to have a suspended solids concentration of 0.8 g/ℓ. Data on suspended solids in disposal area effluents that were presented in Table 5 and Figure 5 indicate that this procedure tends to overestimate the amount of suspended solids in the effluent. However, in view of the fact that there is no other quantitative methodology available, the nomograph is recommended with the understanding that it may lead to conservative designs.

183. In order to control the flow pattern in a disposal area (mainly by reducing the occurrence of short circuiting) and thereby improve the hydraulics of the sedimentation basin systems of barrier or buffer or spur dikes can be constructed inside the disposal area. Although the recommendation of methods for designing such systems is not within the scope of this work, the nomographs of Figures 32 and 33 can be used for any disposal area for which surface area can be estimated.

Filter Systems

184. Since sedimentation alone, whether or not aided by chemical coagulation and flocculation, can not always produce effluents of

acceptable quality, there will be cases where the use of a filter system or combination of systems is necessary. In Appendix D a variety of conventional filter systems were reviewed, and those with potential application in the design of dredged material disposal areas were selected. Furthermore, three different systems were developed (Part V) on the basis of the experimental investigation presented in Parts III and IV. In the following paragraphs these systems are discussed with emphasis on the conditions under which they can be used and the results that can be expected; also presented are graphs that have been developed to expedite the design of these new systems.

Vacuum filtration

185. Based on a review of available literature, vacuum filtration systems have been identified as the only conventional designs that are capable of dewatering dredged material slurries. The influent to such systems can have suspended solids contents from 1 to 10 percent by weight (or 10 to 100 g/ℓ), and appropriately designed systems can produce effluents with suspended solids as low as 0.5 g/ℓ with removal efficiencies that can be 99 percent or more but rarely exceed 90 percent. The factor that may render vacuum filtration economically unfeasible is the limited yield per unit surface area of the filter; hence, large filter surface areas are required to handle the large volumes of effluents that are anticipated. In this respect, rotary disk vacuum filters have a significant advantage over rotary drum vacuum filters, because the surface area of the former is up to five times that of the latter, thereby reducing the space requirements, as well as the capital, maintenance, and operating costs, and increasing the versatility of the system.

186. Vacuum filters can be incorporated in the design of disposal areas where the detention time is too short for effective sedimentation of suspended solids. This would be typical of disposal facilities characterized as transfer stations, where dredged material slurries must be dewatered at a fast rate and the resulting solids transferred to other locations for temporary or permanent storage. Depending on the frequency and duration of dredging seasons, two alternative concepts can be advanced. One is a permanent, land-based installation that dewaters slurries from

which the large-size particles (sands and gravels) have been removed (perhaps by coarse sedimentation). Another is an installation on a barge or any other floating structure than can translocate with the dredge. A land-based facility may be more economical in areas where considerable dredging takes place annually; whereas a barge-based facility may be appropriate for smaller operations where dredging is infrequent and the volumes are relatively small. In regions where strict effluent quality standards must be satisfied, the effluent of vacuum filters will probably be unacceptable for discharge in the open waters and a second system would probably be required to polish the effluent.

Microscreening

187. It was concluded in Appendix D that conventional microscreen or microstrainer units are inappropriate for reducing suspended solids in disposal area effluents, but the Sonic Strainer Micro Screen described in Appendix D (marketed by the FMC Corporation) may be a single example of an appropriate microscreen system. The Sonic Strainer is reported to be capable of handling influents with suspended solids ranging from as low as 10 mg/ℓ to as high as 20 g/ℓ with removal efficiencies from 90 to 99 percent for particles larger than 1μ. However, at high concentrations of suspended solids, the throughput capacity of the system is reduced substantially and a large number of units would be required.

188. The Sonic Strainer might be used at moderate-sized disposal areas that have the following characteristics: (a) a substantial coarse fraction of the slurry solids are removed by sedimentation; (b) the amount of submicron particles is negligible; and (c) strict effluent quality standards are enforced. Alternatively, the Sonic Strainer might serve to polish vacuum filter effluents. In any case, provisions must be made to move the device as the concentrated solids that are rejected by it build up in its vicinity; otherwise, the device will lose efficiency and throughput capacity, even if it is not bogged down by its own waste stream. Possibly the unit could be mounted on a raft inside the disposal area, and it may be economical to transport this system from one disposal area to another.

Mechanized deep-bed filters

189. Conventional mechanized granular media filter have never been designed to clarify waters with high concentrations of suspended solids; they are viewed herein only as a possible alternative to nonmechanized systems, which require high maintenance and frequent removal or cleaning of the filter media. In such cases a backwashing system, possibly automated, will be necessary.

New designs

190. The conceptual development of three different types of nonmechanized granular media filters (pervious dike, sandfill weir, and cartridge) was presented in Part V with design guidelines and a typical design example. For a given set of operating conditions, the design of one of these systems requires the specification of two basic items of information: namely, the type of filter medium to be used and the time required for the filter medium to function before clogging.

191. Selection of filter medium. By comparing the quality of the filter influent to the desired quality of the effluent, the required removal efficiency of a filter system can be computed. The height of the confining dike and/or the maximum difference in elevation between the water inside and outside the confining structure permits an accurate estimate of the filter depth. When the removal efficiency and the filter depth are known, the effective grain size of the filter medium can be computed by using Equations 1, 3a, and 3b. Figure 34 was prepared to expedite the process of selecting the appropriate filter medium. By entering the ordinate scale with the desired removal efficiency and proceeding to the appropriate filter depth, the effective grain size can be read from the abscissa; alternatively, for a given filter medium, the required filter depth can be estimated.

192. Clogging time. Filter media become ineffective and require cleaning or replacement for either or both of two reasons: grains become coated by the captured solids, thereby lowering the clarification efficiency to unacceptable levels, or the voids become filled with captured solids to such an extent that the permeability of the filter bed is reduced by perhaps orders of magnitude. Data from the experimental

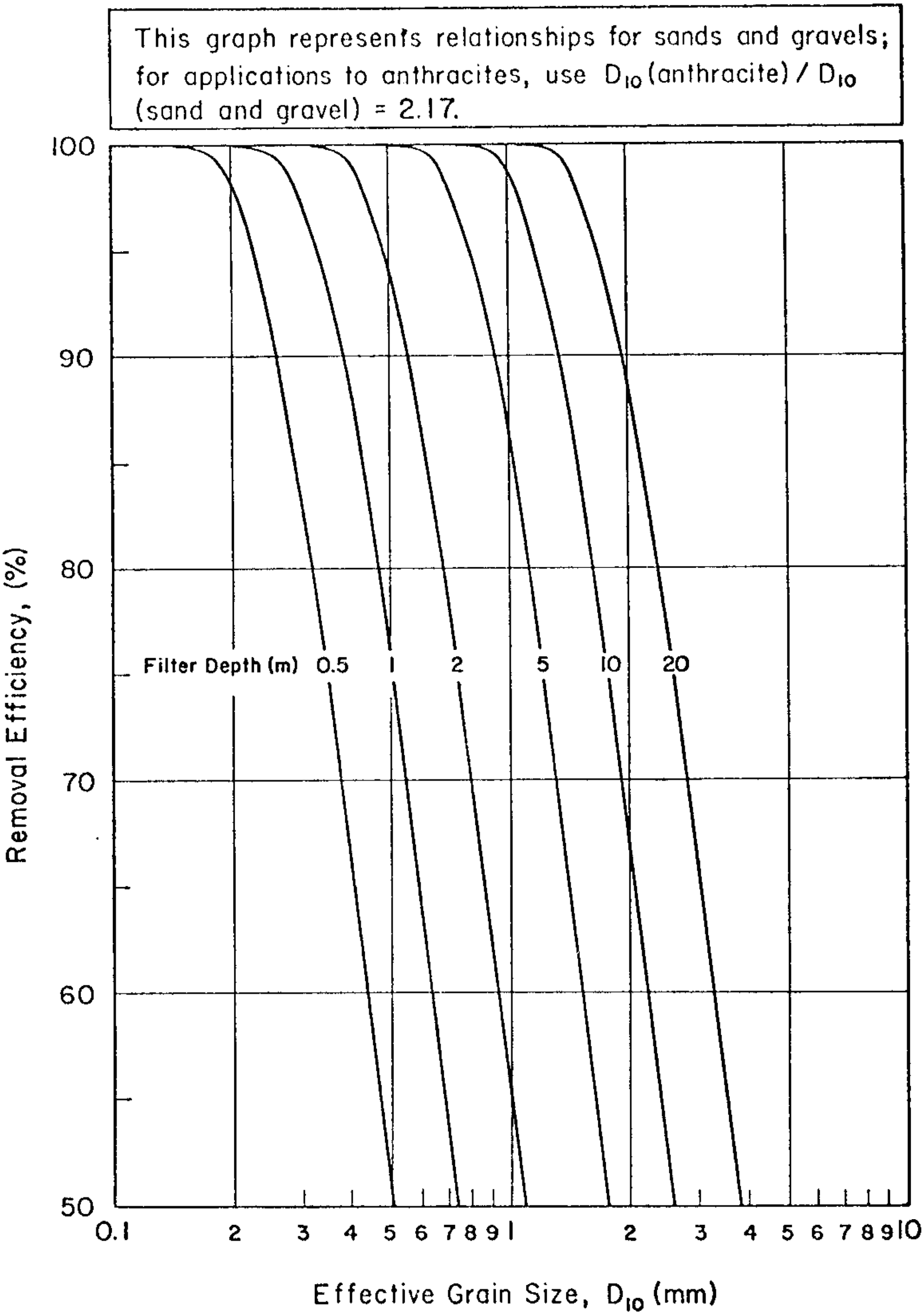

Figure 34. Relationships Among Removal Efficiency, Depth, and Effective Grain Size of Filter

program of this study allow the following conclusions to be advanced:

a. Sands or gravels and anthracites with effective grain sizes larger than 2 and 3 mm, respectively, experience no clogging; this is due primarily to their limited removal efficiency.

b. Sands or gravels and anthracites with effective grain sizes smaller than 2 and 3 mm, respectively, experience clogging due to excessive reduction in void space and consequent reduction in permeability.

c. Measurements of the specific deposit (weight of retained solids per unit volume of filter bed) showed that, for all practical purposes, the retained solids were uniformly distributed along the filter depth (equal to about 1.5 m) upon completion of a filter run.

d. Both sands and anthracites showed clogging signs when the specific deposit reached an average value of about 0.3 g/cm^3; the actual values for individual cases varied from about 0.2 to about 0.4 g/cm^3.

193. The period of time that is required for an initially clean filter bed to manifest severe clogging can be computed on the basis of the solids loading and removal efficiency of the filter. Based on experiments described in Part IV, it was found that the filter medium will begin to show signs of severe clogging when the specific deposit reaches a certain value. Therefore, the problem of determining the effective lifetime of a filter bed can be stated as follows: for given values of required removal efficiency, suspended solids concentration of the influent and filter depth, determine the volume of effluent that can be filtered before the specific deposit reaches a certain value.

194. To expedite the determination of such filtrate volumes, the graph presented in Figure 35 was developed on the basis of the following assumptions: (a) the limiting value of the specific deposit is 0.3 g/cm^3 and (b) the distribution of the deposit in the filter bed is uniform with depth. All computations are based on a unit cross section (1 m^2) of filter. Within this framework it follows that (a) the total mass retained up to the point of severe clogging is equal to the product of the filter volume and the specific deposit; (b) the mass retained per unit volume (1 m^3) of filtrate is equal to the product of the removal efficiency and the amount of solids in a unit volume of influent; and (c) the ratio of

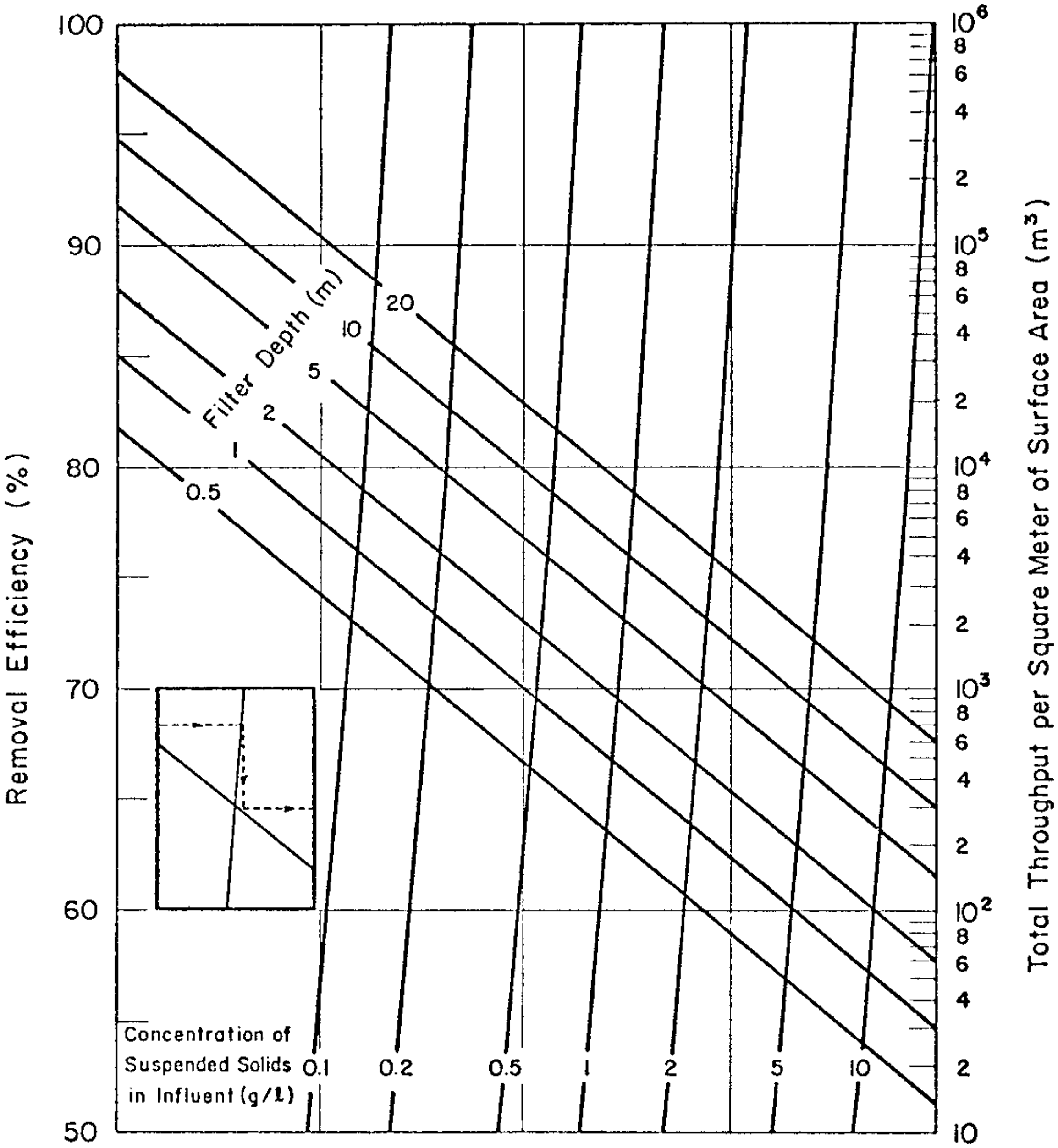

Figure 35. Relationships Among Removal Efficiency and Depth of Filter, Concentration of Suspended Solids in Influent, and Total Throughput Before Clogging

the total mass to the mass retained per unit volume of filtrate is equal to the volume of the throughput before clogging. To use Figure 35 the designer must take the following steps:

a. Enter the graph with the required removal efficiency.

b. Move to the right until the appropriate curve representing the concentration of suspended solids in the influent is reached.

c. Proceed vertically until encountering the curve giving the appropriate filter depth.

d. Exit at the right and read total throughput volume of suspension per unit surface area (1 m^2) before severe clogging occurs.

Synthesis

195. In Part V, Appendix D, and the foregoing parts of Part VI, concepts were developed for use in the design of systems for dewatering dredged material slurries and clarifying disposal area supernatants. Outlines of the steps to be followed in the decision making process are given succinctly in Figures 36 through 40. The use of these flow charts should considerably simplify the selection of the appropriate combinations of solid-liquid separation systems for application to a given disposal area.

196. It is evident that the effect of sedimentation should be considered first (Figure 36) in order to judge whether or not the effluents from a given disposal area are acceptable for discharge to the receiving water from a suspended solids standpoint. Estimates of the concentration and gradation of suspended solids in the effluent from a disposal area can be obtained from Figures 32 and 33. A comparison of the concentration A with the required effluent quality B allows a decision to be made with respect to the need for further treatment. Figures 37 through 40 outline alternative courses of design according to the amount of suspended solids in the effluents after the largest available sedimentation basin has been utilized. However, as shown in Figure 39, it may occasionally be preferred to limit the size of the disposal area to a presedimentation basin

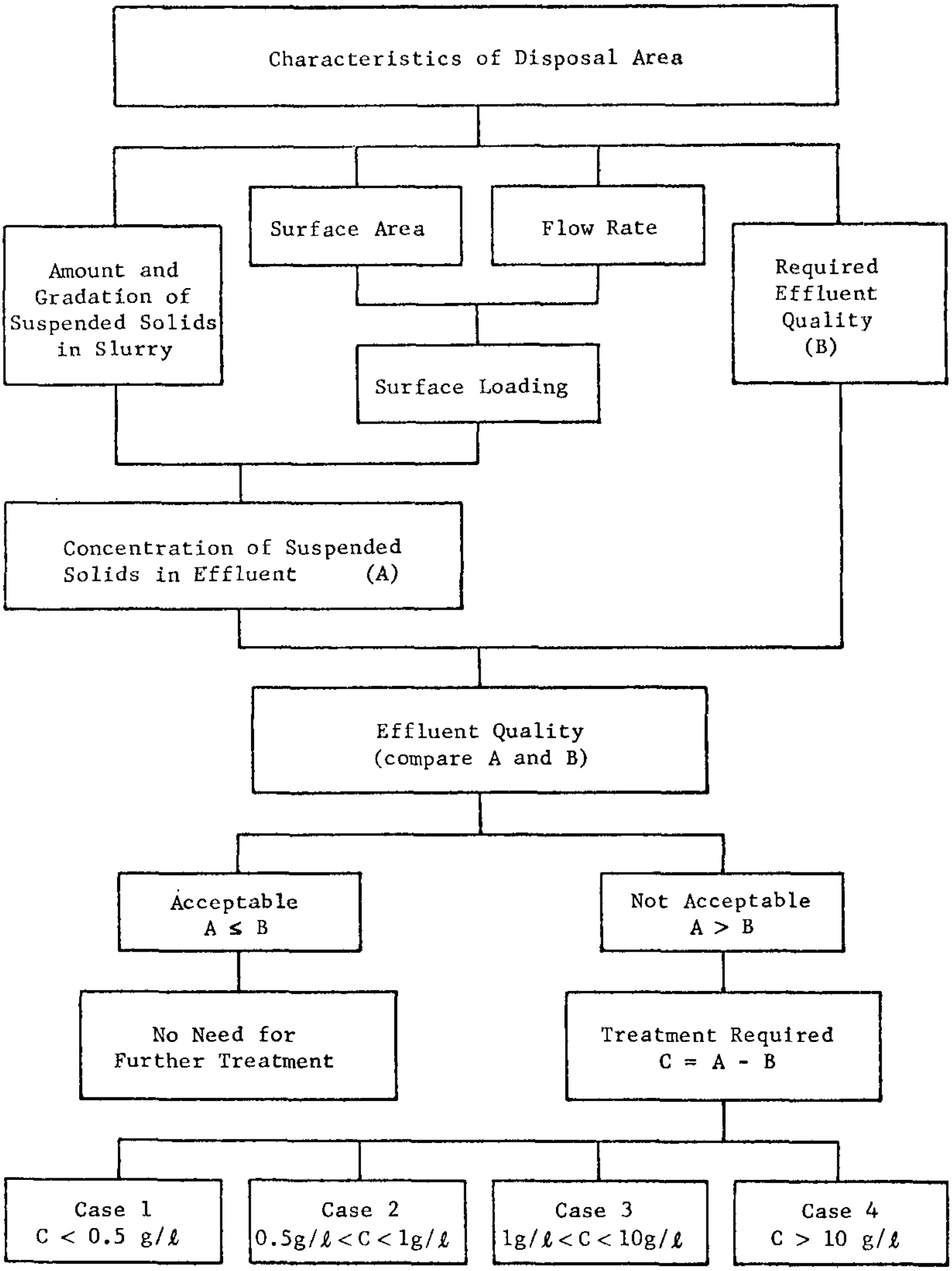

Figure 36. Flow Diagram of Alternative Courses of Action to Evaluate Effect of Sedimentation of Disposal Area Effluents

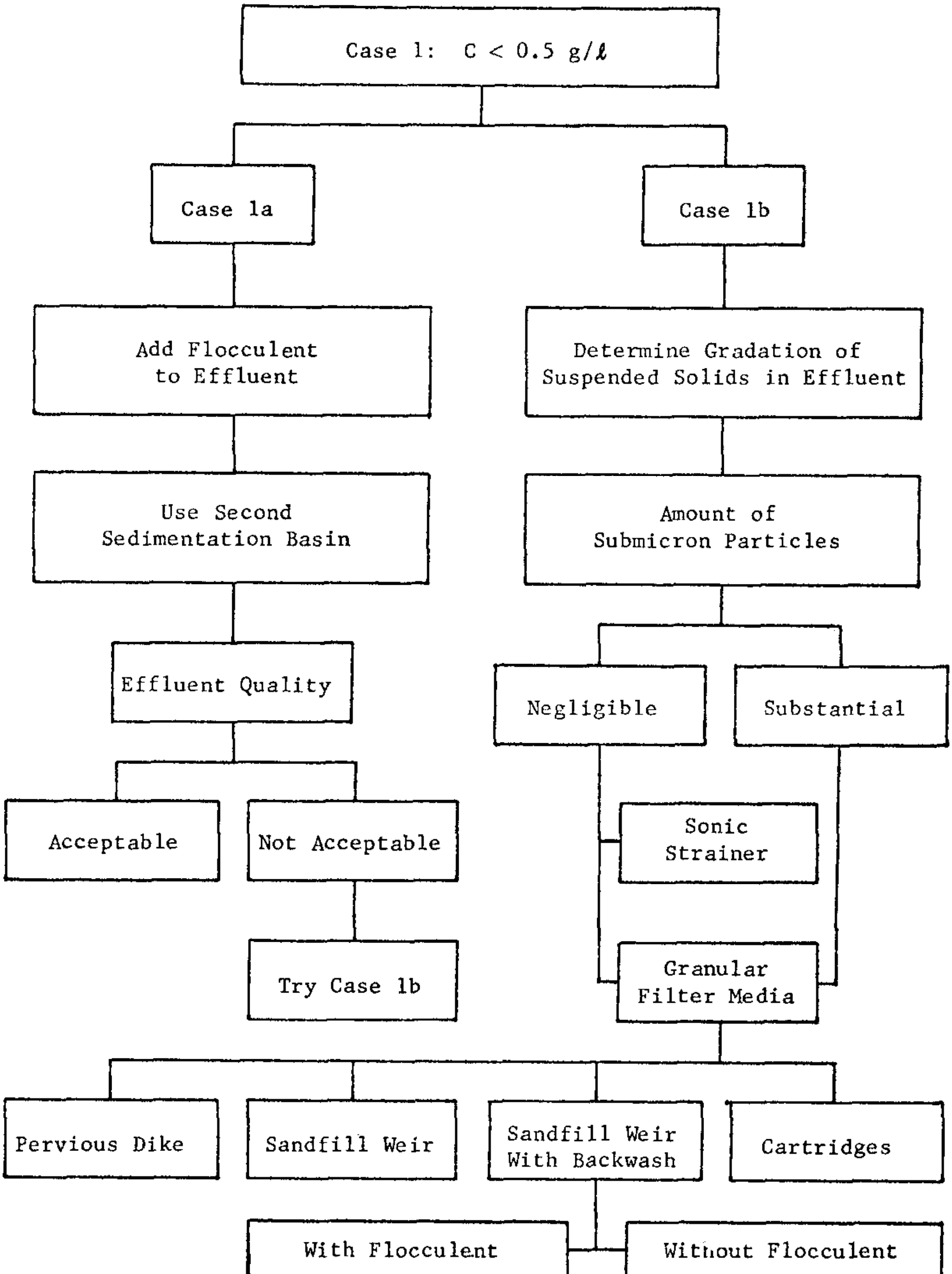

Figure 37. Flow Diagram for Case 1

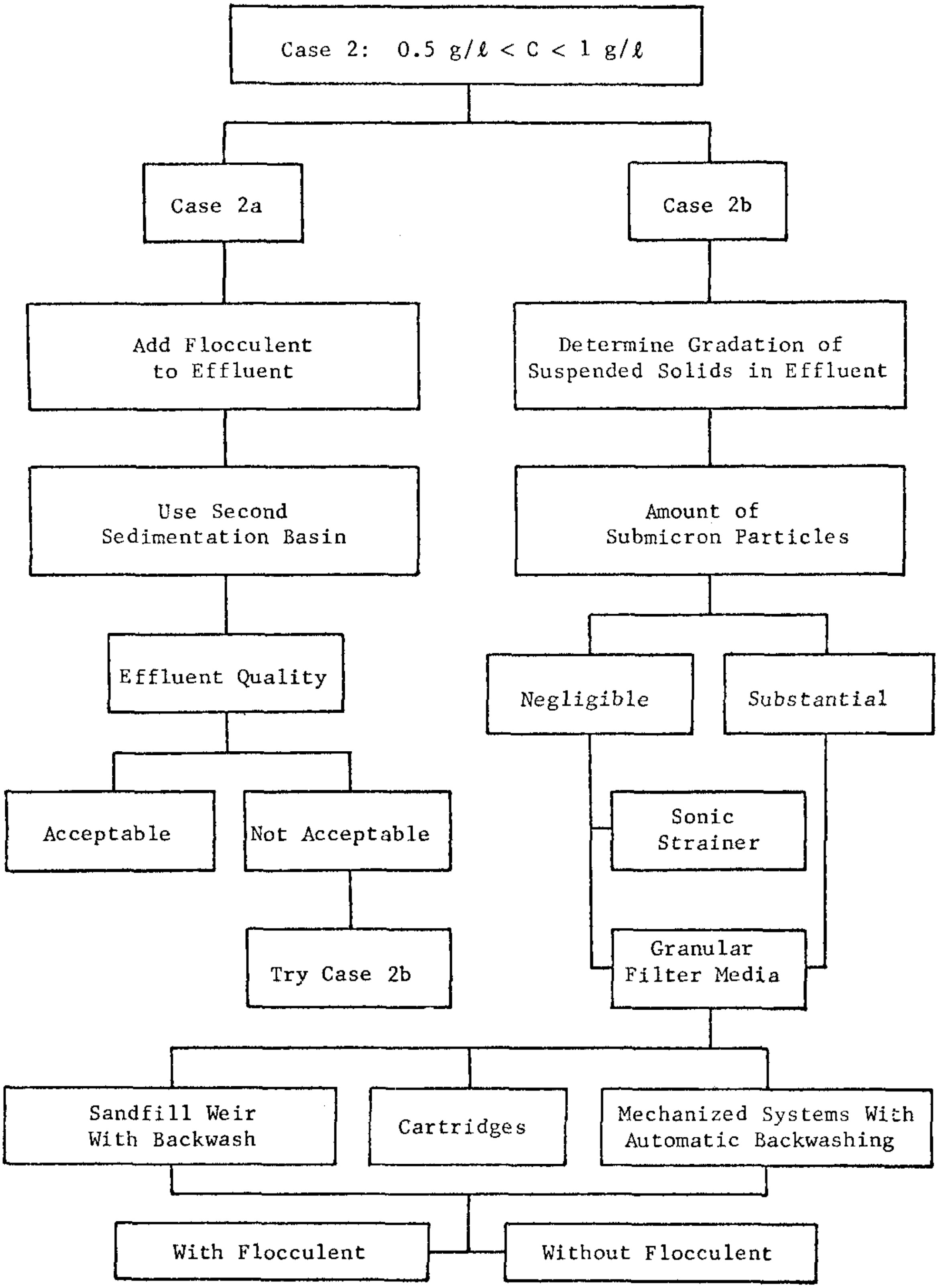

Figure 38. Flow Diagram for Case 2

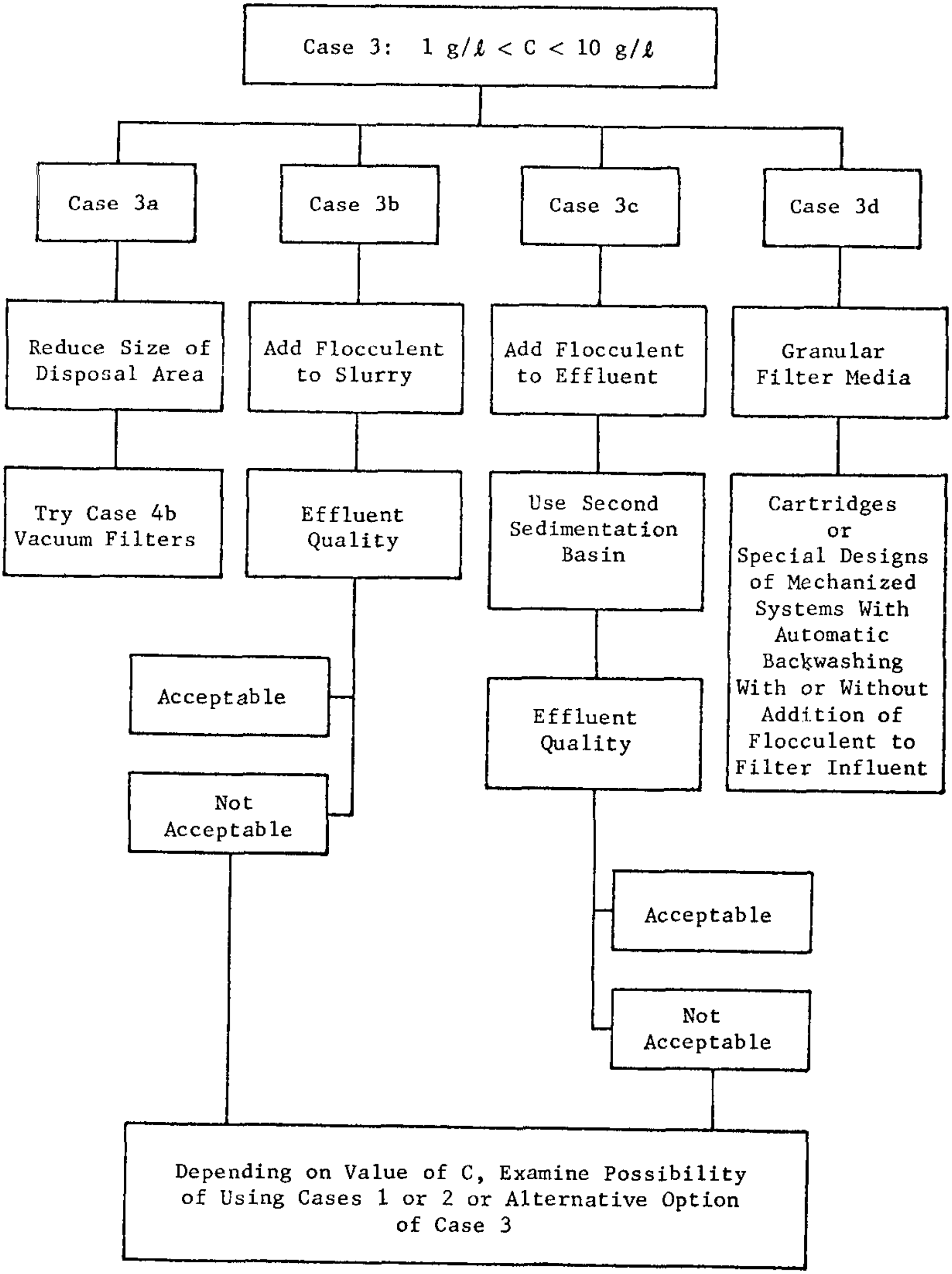

Figure 39. Flow Diagram for Case 3

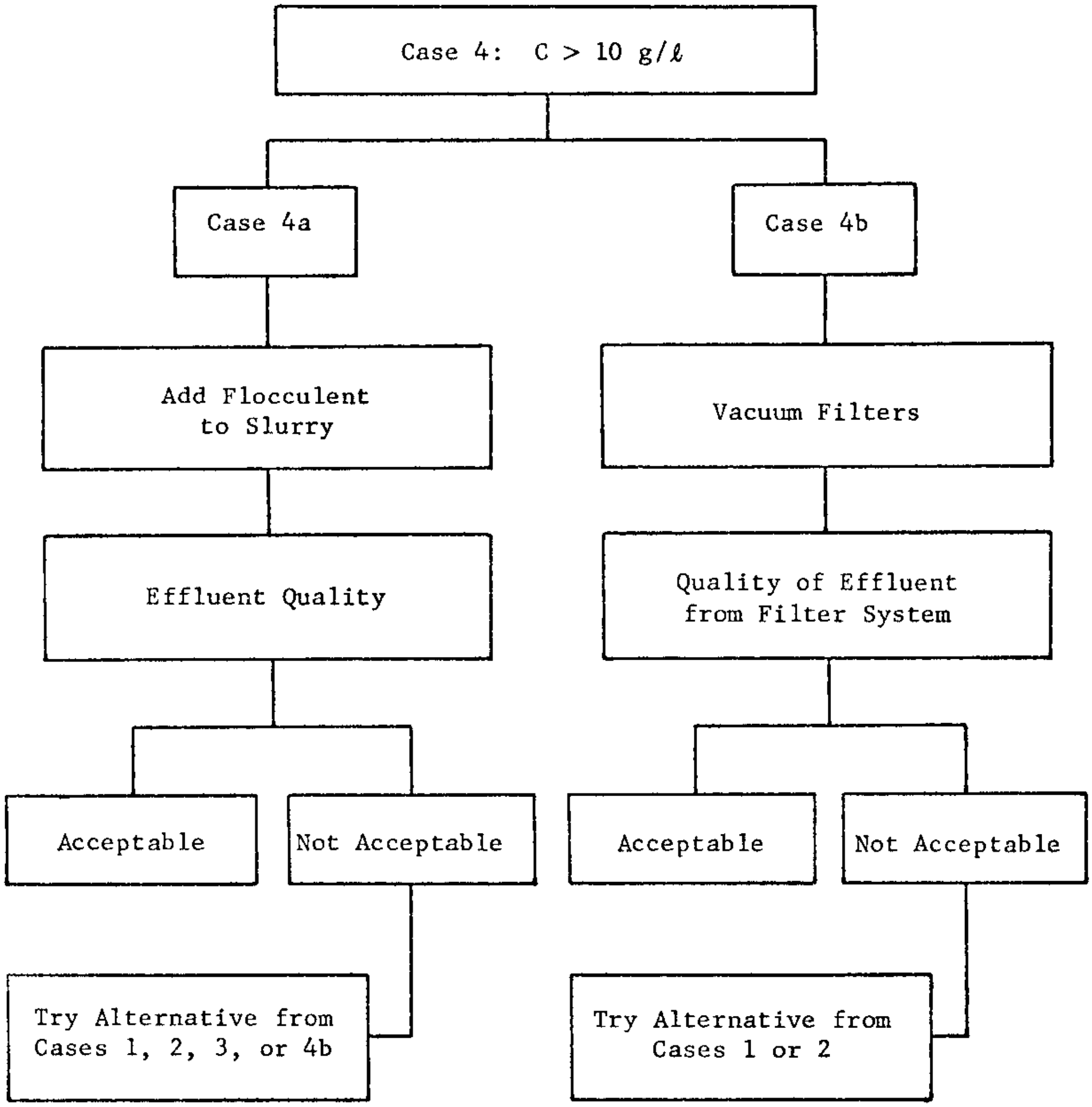

Figure 40. Flow Diagram for Case 4

prior to a vacuum filter dewatering operation. Since vacuum filters operate more efficiently at suspended solids loads above 1 per cent (10 g/ℓ), a rather small basin could produce an effluent suspension with 2 to 4 per cent solids, and this would be the vacuum filter influent. For larger basins, thickening would be required prior to vacuum filtration, and such redundant operations would clearly be inefficient.

197. If a flocculant is added to the dredged material slurry at the time that it is pumped into the disposal area, the sedimentation rates will be increased and cleaner effluents will be produced. Lime is one additive that appears to produce good results when used to treat dredged material slurries directly. Organic polymers have also been found to be excellent flocculants for disposal area supernatants with no more than 20 g/ℓ suspended solids. However, when treating disposal area effluents with a flocculant, it is necessary to provide a second sedimentation basin where gravity clarification can take place. In general, the effective use of flocculation as a solid-liquid separation scheme requires that samples of bottom sediments be obtained and tested with various flocculants to determine the best additive and some optimal range of doses.

198. Based on available information, the operating conditions and performance capabilities of vacuum filtration equipment, the Sonic Strainer Micro Screen, granular media filters with backwash, and the new conceptual designs of a pervious dike, sandfill weir with or without backwash, and granular media cartridge have been described in Appendix D and Part V. However, field pilot studies are suggested to permit a better estimation of the full-scale cost-effectiveness of each alternative. Such tests should precede the incorporation of any of these designs into a full-scale operation in order to better ascertain the design life and maintenance and operational costs.

199. Figures 34 and 35 present nomographs that have been developed to assist the designer in selecting the type of filter medium and estimating the effective lifetime of a filter. However, the development of these nomographs is based on two important assumptions that (a) the limiting specific deposit is 0.3 grams of solids per cm^3 of filter media and (b) the mass of solids retained in the filter is independent of the

grain-size distribution of the filter influent. Both of these assumptions were established on the basis of the laboratory data presented in Part IV, and they were found to be consistent with the field (Toledo, Ohio and Wilmington, North Carolina) test data also presented in Part IV. Despite this limited verification, it must be recognized that these assumptions may not hold for other dredged material slurries encountered in various dredging operations, and pilot tests are therefore recommended to ascertain their applicability prior to the unqualified acceptance of the design procedure outlined herein.

Summary

200. Guidelines for the application of solid-liquid separation technology to the design of dredged material confinement facilities were summarized in this part. Several nomographs and figures were prepared to expedite the design of a particular filter system, and flow diagrams with step-by-step instructions were given to provide direct and rapid insight into possible alternative courses of design. The basic information consists of (a) a graph for use in estimating the gradation of suspended solids in disposal area effluents, (b) a nomograph for determining the concentration of suspended solids in the effluent from the sedimentation portion of a disposal area, (c) a graph for selecting appropriate granular filter media for design, (d) a graph for estimating the clogging time of a granular media filter, and (e) several flow charts to be used as a decision-making guide in the application of solid-liquid separation technology to the design of disposal areas for dredged material.

PART VII: SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Summary

201. Increasingly stricter environmental standards are being imposed to mitigate or prevent waterborne contaminants of many varieties emanating from dredged material disposal areas from entering the adjacent receiving waters. Waterborne suspended solids are in themselves a major contaminant, as well as a carrier for absorbed, precipitated, or exchanged contaminants in the effluents from dredged material confinement facilities. Hence, improved methodology to control and reduce the level of suspended solids in these effluents is considered a necessity, and the research reported herein was conducted in response to this need. A dual-faceted program was undertaken to (a) investigate the feasibility of using concepts already established in modern solid-liquid separation technology and (b) develop new or modified concepts for suspended solids control. This part summarizes the results of this research, presents the major conclusions that were deduced, and outlines recommendations for follow-up research and development.

202. An extensive background study was undertaken to provide the basis for the experimental part of this research and to place the problem of suspended solids control in dredged material disposal operations in perspective with modern solid-liquid separation technology. Disposal area design and operation was reviewed from the standpoint of effluent quality control, and physical and chemical characterization data for dredged material were collected from a large number of locations. In addition, conventional filtration techniques and previous research on the filtration of clay suspensions were examined. Based on information assembled during this part of the investigation, an extensive program of laboratory and field filtration tests on granular and fibrous media was planned and executed. The purpose of this experimental investigation was primarily to determine the characteristics and performance capabilities of filter media that could be employed as components of filter systems for effluent quality control in disposal area operations. Pursuant to an analysis of the results obtained, criteria and guidelines were advanced to facilitate the appropriate selection and use of the filter media that were investigated.

203. The rapid evolution in dredged material disposal and re-use concepts, as well as the wide range of conditions and materials encountered, dictated that the problem of effluent quality control be treated as a complete solid-liquid separation problem and not simply as one of selecting an appropriate filter system. Within this framework the solution requires the judicious combination of some methodology for dewatering dredged material slurries and/or clarifying the disposal area supernatants. Although the dewatering problem can probably be handled by either sedimentation or mechanical filtration, the resulting waters may require clarification by some other type of filter system. Hence, the beneficial effects of sedimentation and flocculation on clarification were given considerable attention; the compatibility, advantages, and disadvantages of conventional filter systems were discussed; and, as a result of the experimental study, new concepts were developed for the design of pervious dikes, sandfill weirs with and without backwash, and granular media cartridges. Nomographs were prepared for use in the design of the latter systems, as well as for assessing the extent of clarification achieved by sedimentation, and a general methodology in the form of flow charts was proposed as a guide to facilitate the selection of the most appropriate technique for controlling effluent quality.

204. When assessing the effectiveness of a given filter system it is important to recognize that each system is associated with an acceptable range of influent suspended solids; a few systems operate effectively at high levels of suspended solids (> 10 g/ℓ), several at intermediate levels, and a few at low levels (< 1 g/ℓ). As defined herein, good or effective clarification is considered to correspond to removal efficiencies of 90 percent or more in the intermediate to low ranges of influent suspended solids. Obviously, the specific quality of the effluent from a given filter system is directly dependent on the amount of influent suspended solids. For example, although a system may have 95 percent removal efficiency, it may still not satisfy a strict effluent standard (such as 50 mg/ℓ) if the influent solids are 5 g/ℓ. Accordingly, the proper exercise of engineering judgment is indispensible to the optimal usage of the alternatives available.

Conclusions

205. Based on the background study, the analysis of the results obtained from the experimental investigation, and an extensive review of pertinent literature, the following conclusions can be advanced:

a. High variability in disposal area geometry, nature of bottom sediments, slurry pump-in operations, and effluent quality standards complicate to a severe degree the problem of effluent quality control in dredged material containment facilities and preclude the development of a unique or universal solution to the problem.

b. Disposal area effluent quality control should be considered as a general solid-liquid separation problem that consists of dewatering dredged material slurries and/or clarifying disposal area supernatants.

c. Although no formal methodology is available to predict directly the expected sedimentation patterns in disposal areas, the adaptation of classical sedimentation basin theories to disposal area operating conditions allows a first-order approximation of the amount and gradation of suspended solids in disposal area effluents.

d. For a given flocculant, different dredged material show different behavior, and pilot programs are needed to establish the basis for appropriate additives and doses. In general, when treating suspensions with 50 g/ℓ or more suspended solids content, lime appears to be the most effective of either inorganic or organic chemicals, but for dredged material slurries with suspended solids concentrations up to 20 g/ℓ, organic polymers are probably the most effective and least expensive.

e. The behavior of sands, gravels, and anthracites in the filtration of suspensions in fresh or saline waters appears to be generally similar, except that anthracites show a slightly better mass and small particle size removal efficiency in saline environments.

f. Certain vacuum filtration technology appears to be technically feasible for dewatering dredged material slurries with 10 g/ℓ or more suspended solids content, but it will probably not be economically acceptable in many cases. Furthermore, depending on effluent quality standards, it may be necessary to incorporate another filter system to polish the filtrates produced by vacuum equipment.

g. Special designs of mechanized surface filtration systems, such as belt filters operating under capillary or squeezing action, may function effectively under influent conditions similar to those described for vacuum filters, and they may offer savings in capital and operating costs. However, additional studies are needed to evaluate these benefits more fully.

h. Special designs of automated granular media filters, such as moving bed, upflow, or pressure systems, are technically capable of clarifying waters with suspended solids loads up to 10 g/ℓ, but such systems will have very short filter cycles, require extensive cleaning, and probably prove to be economically unfeasible for loads above 1 or 2 g/ℓ.

i. Granular media cartridges can be used to clarify supernatants with suspended solids concentrations up to about 10 g/ℓ; however, for concentrations above 1 g/ℓ, maintenance will probably be excessive.

j. A special microscreen filter can be used to clarify supernatants with high variability in the concentration of suspended solids (up to several grams per liter solids content), but it is most effective for concentrations below 1 g/ℓ and for suspended particles greater than 1 μ in diameter.

k. Sandfill weirs with backwash can be used to clarify supernatants with suspended solids concentrations up to about 1 or 2 g/ℓ.

ℓ. Conventional automated granular media filters can handle influents with suspended solids loads up to 1 g/ℓ, but they normally perform most effectively and economically at much lower concentrations.

m. Pervious dikes and sandfill weirs without backwash are considered adequate for use with supernatants that have no more than 0.5 g/ℓ suspended solids.

n. Fibrous media do not appear to be technically feasible as components of nonmechanized, low-maintenance filter systems.

o. Slow sand filters and intermittent sand filters are unfeasible for use in disposal area operations because of their ability to handle only influent solids levels that already meet strict effluent standards.

p. At its present stage of development, electrofiltration is probably technically feasible, but is in no way an economic alternative for dewatering or clarifying supernatants from dredged material containment areas.

q. Mechanized cloth or screen filters, such as drums or belts, operating only under gravity head are not effective for dewatering dredged material or for clarifying the supernatants.

Recommendations

206. As a consequence of the knowledge acquired and experience gained during the conduct of this research, the following recommendations are offered for further investigations:

- a. Long-term filtration tests (runs of weeks or months) should be conducted on a few highly selective granular media to evaluate more completely their performance capabilities under the antagonistic or synergistic natural environments in which they must operate; results of this type would enable some of the necessary extrapolation employed in this investigation to be avoided.
- b. Full-scale pilot tests on pervious dikes, sandfill weirs, and granular media cartridges should be conducted at a number of disposal areas with different operating conditions; experience records of this type are needed for the effective evaluation of the soundness of the methodology advanced in this study.
- c. Vacuum filtration should be thoroughly investigated with respect to both technical and economical feasibility, particularly with respect to applications in transfer stations and areas with infrequent dredging operations.
- d. Since the selection of chemicals that are universally applicable and equally effective in flocculating all varieties of dredged material is virtually impossible, a methodology (perhaps akin to the standard "jar test" employed in water process technology) should be developed to enable the proper flocculant, together with optimum dosage, to be selected for a given dredged material.
- e. The possibility of using relatively inexpensive and readily available nonconventional filter media, such as straw or wood chips, should not be precluded on the basis of the somewhat unfavorable preliminary evidence reported herein. More comprehensive investigations should be undertaken to assess completely their technical applicability and economical feasibility.
- f. Since the experimental phase of this research program was performed almost totally on suspensions of inorganic clays, the filtration of suspensions with very high suspended organic solids content should be studied to identify and evaluate the potential adverse effects of various amounts of organics on the performance characteristics of granular media filter systems.
- g. A number of technically feasible filtration alternatives involve the consumption of energy by system components,

and, in view of the fact that disposal areas are often located in isolated regions where conventional power supply is not available, a feasibility study of alternative nonconventional power sources, such as wind, solar, or tidal energy, should be undertaken.

REFERENCES

1. Agrawal, G. D. (1966), Electrokinetic Phenomena in Water Filtration, Ph.D. Thesis, University of California, Berkeley.

2. Akers, R. J. (1975), "Filtration Pretreatment," The Scientific Basis of Filtration, Volume 2, Chapter 14, Nordhoff Press, Leyden, The Netherlands.

3. Alt, C. (1975), "Practical Problems in Choosing Filtration Process and Filter Developments," The Scientific Basis of Filtration, Volume 2, Chapter 16, Nordhoff Press, Leyden, The Netherlands.

4. Atmatzidis, D. K. (1973), A Study of Sand Migration in Gravel, M.S. Thesis, Department of Civil Engineering, Northwestern University, Evanston, Illinois.

5. Bertram, G. E. (1940), An Experimental Investigation of Protective Filters, Publication Number 267, Graduate School of Engineering, Harvard University, Cambridge, Massachusetts.

6. Boyd, M. B., Saucier, R. T., Keeley, J. W., Montgomery, R. L., Brown, R. D., Mathis, D. B., and Guice, C. J. (1972), Disposal of Dredge Spoil. Problem Identification and Assessment and Research Program Development, Technical Report H-72-8, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

7. Burd, R. S. (1968), A Study of Sludge Handling and Disposal, Publication WP-20-4, U.S. Department of Interior, Federal Water Pollution Control Administration, Washington, D.C.

8. Burns and Roe, Inc. (1971), Process Design Manual for Suspended Solids Removal, by Burns and Roe, Inc. to the Environmental Protection Agency, Program 17030-GNO, Oradell, New Jersey.

9. Calhoun, C. C., Jr. (1972), Development of Design Criteria and Acceptance Specifications for Plastic Filter Cloths, Technical Report S-72-7, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

10. Camp, T. R. (1946), "Sedimentation and Design of Settling Tanks," Transactions of the American Society of Civil Engineers, Volume 111, Number A51, pp. 895-936.

11. Cedergren, H. R. (1962), "Seepage Requirements of Filter and Pervious Bases," Transactions of the American Society of Civil Engineers, Volume 127, Part 1, pp. 1090-1113.

12. Chang, S. C. (1972), Simulation Model of Flocculant Settling, Ph.D. Thesis, Northwestern University, Evanston, Illinois.

13. Cleasby, J. L. (1969), "Approaches to Filterability Index for Granular Filters," Journal of the American Water Works Association, Volume 61, Number 8, pp. 372-381.

14. Cleasby, J. L. (1972), "Behavior of Deep Granular Filters," Industrial Water Engineering, Volume 9, Number 1, pp. 32-36.

15. Cooper, F. C., Mees, Q. M., and Bier, M. (1965), "Water Purification by Forced Flow Electrophoresis," Journal of the Sanitary Engineering Division, American Society of Civil Engineers, Volume 91, Number SA6, pp. 13-25.

16. Creager, W. P., Justin, J. D., and Hinds, J. C. (1955), Engineering for Dams, Volume III, Earth, Rockfill, Steel, and Timber Dams, John Wiley & Sons, Inc., New York, New York.

17. Deb, A. K. (1969), "Theory of Sand Filtration," Journal of the Sanitary Engineering Division, American Society of Civil Engineers, Volume 95, Number SA3, pp. 399-422.

18. Dickey, G. E. (1961), Filtration, Reinhold Publishing Corporation, New York, New York.

19. Dravo Corporation (1970), Deep-bed Filtration Systems, Bulletin Number 70WWT02, Pittsburgh, Pennsylvania.

20. Eckenfelder, W. W., Jr. (1970), Water Quality Engineering for Practicing Engineers, Barnes and Noble, New York, New York.

21. Ecodyne Corporation, Graver Water Conditioning Company (1971), Automatic Gravity Filtration-Monovalve Series, Reference Catalog WC133B, Union, New Jersey.

22. Edwards, D. M., and Monke, E. J. (1967), "Electrokinetic Studies of Slow Sand Filtration Process," Journal of the American Water Works Association, Volume 59, Number 10, pp. 1310-1319.

23. Emmett, R. C., and Silverblatt, C. E. (1974), "When to Use Continuous Filtration," Chemical Engineering Progress, Volume 70, Number 12, pp. 38-42.

24. Environmental Protection Agency (1970), Dilute Spent Kraft Liquor Filtration through Wood Chips, School of Forest Resources, University of North Carolina, Raleigh, North Carolina.

25. Environmental Protection Agency (1973), "Ocean Dumping; Final Regulations and Criteria," Federal Register, Volume 38, Number 198, pp. 28610-28621.

26. Environmental Protection Agency (1974), Process Design Manual for Sludge Treatment and Disposal, Technology Transfer Series, 625/1-74-000.

27. Environmental Protection Agency (1975a), Navigable Waters-Discharge of Dredged or Fill Material," Federal Register, Volume 40, Number 173, pp. 41292-41298.

28. Environmental Protection Agency (1975b), Process Design Manual for Suspended Solids Removal, Technology Transfer Series, 625/1-75-003a.

29. Fair, G. M., and Geyer, J. C. (1966), Water Supply and Waste-Water Disposal, John Wiley & Sons, Inc., New York, New York.

30. Felderman, J. E., and Eno, B. E. (1975), "Prediction of Sedimentation Patterns in a Typical Great Plains Prairie Lake, Fifth Annual Environmental Engineering and Science Conference, Louisville, Kentucky.

31. Filipkowski, W. F., and Strudgeon, G. E. (1973), "A New Filtration System for Tertiary Treatment of Refinery Wastes at Marathon Oil Refining Robinson, Illinois," Paper presented at the Water and Wastewater Equipment Manufacturer's Association Industrial Water and Pollution Conference and Exposition, Chicago, Illinois.

32. Fitch, B. (1974), "Choosing a Separation Technique," Chemical Engineering Progress, Volume 70, Number 12, pp. 33-37.

33. FitzPatrick, J. A. (1972), Mechanisms of Particle Capture in Water Filtration, Ph.D. Thesis, Harvard University, Cambridge, Massachusetts.

34. FitzPatrick, J. A., and Spielman, L. A. (1973), "Filtration of Aqueous Latex Suspensions through Beds of Glass Spheres," Journal of Colloid and Interface Science, Volume 43, Number 2, pp. 350-369.

35. FMC Corporation, Environmental Equipment Division (1973), Up-flow Sand Filter, Bulletin 9030, Chicago, Illinois.

36. Ghosh, G. (1958), "Mechanism of Rapid Sand Filtration," Water and Water Engineering, Volume 62, Number 746, pp. 147-153.

37. Hazen, A. (1904), "On Sedimentation," Transactions of the American Society of Civil Engineers, Volume 53, pp. 53-63.

38. Heertjes, P. M., and Lerk, C. F. (1967), "The Functioning of Deep Bed Filters, Part II: The Filtration of Flocculated Suspensions," Transactions of the Institute of Chemical Engineers, Volume 45, T129-T145.

39. Herzig, J. P., LeClerc, D. M., and LeGoff, P. (1970), "Flow of Suspensions through Porous Media - Application to Deep Filtration," Industrial and Engineering Chemistry, Volume 62, Number 5, pp. 8-35.

40. Hudson, H. E., Jr. (1959), "Declining Rate Filtration," Journal of the American Water Works Association, Volume 51, Number 11, pp. 1455-1463.

41. Hummel, P. L., and Krizek, R. J. (1974), "Sampling of Maintenance Dredgings," Journal of Testing and Evaluation, American Society for Testing and Materials, Volume 2, Number 3, pp. 139-145.

42. Hunter, R. J., and Alexander, A. E. (1963), "Surface Properties and Flow Behavior of Kaolinite; Part III; Flow of Kaolinite Sols through a Silica Column," Journal of Colloid Science, Volume 18, Number 9, pp. 846-862.

43. Ison, C. R. (1967), Dilute Suspensions in Filtration, Ph.D. Thesis, University of London, London, England.

44. Ives, K. J. (1961), "Filtration Using Radioactive Algae," Journal of the Sanitary Engineering Division, American Society of Civil Engineers, Volume 87, Number SA3, pp. 23-37.

45. Ives, K. J. (1969), "Theory of Filtration, Special Subject Number Seven," International Water Supply Congress and Exhibition at Vienna, International Water Supply Association, Vienna.

46. Ives, K. J. (1971), "Filtration of Water and Wastewater," Critical Reviews in Environmental Control, Volume 2, Issue 2, pp. 293-335.

47. Iwasaki, T. (1937), "Some Notes on Sand Filtration," Journal of the American Water Works Association, Volume 29, Number 10, pp. 1591-1602.

48. Jorden, R. H. (1963), "Electrophoretic Studies of Filtration," Journal of the American Water Works Association, Volume 55, Number 6, pp. 771-782.

49. Kavanaugh, M. C., Wright, A. M., Toregas, G., Hallen, L., Selleck, R. E., and Pearson, E. A. (1971), Filtration Kinetics in Water and Wastewater, Second Annual Progress Report, by the University of California to the Environmental Protection Agency, EPA Grant 17030-ECA, Berkeley, California

50. Keeley, J. W., and Engler, R. M. (1974), Discussion of Regulatory Criteria for Ocean Disposal of Dredged Materials: Elutriate Test Rationale and Implementation Guidelines, Miscellaneous Paper D-74-14, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

51. Kjellman, W. (1964), "Unorthodox Thoughts on Filter Criteria," Report Number 6, Paper 1, Preprints and Preliminary Reports of Swedish Geotechnical Institute, Stockholm, pp. 1-11.

52. Krizek, R. J., Gallagher, B. J., and Karadi, G. M. (1974), Water Quality Study for a Dredging Disposal Area, Technical Report Number 4, by Northwestern University to the Environmental Protection Agency, EPA Grants 15070-GCK and R-800948, Evanston, Illinois.

53. Krizek, R. J., Karadi, G. M., and Hummel, P. L. (1973), Engineering Characteristics of Polluted Dredgings, Technical Report Number 1, by Northwestern University to the Environmental Protection Agency, EPA Grants 15070-GCK and R-800948, Evanston, Illinois.

54. Krizek, R. J., Roderick, G. L., and Jin, J. S. (1974), Stabilization of Dredged Materials, Technical Report Number 2, by Northwestern University to the Environmental Protection Agency, EPA Grants 15070-GCK and R-800948, Evanston, Illinois.

55. Krizek, R. J., and Salem, A. M. (1974), Behavior of Dredged Materials in Diked Containment Areas, Technical Report Number 5, by Northwestern University to the Environmental Protection Agency, EPA Grants 15070-GCK and R-800948, Evanston, Illinois.

56. La Mer, V. K. (1964), "Coagulation Symposium Introduction," Journal of Colloid Science, Volume 19, Number 4, pp. 291-293.

57. Libby, D. V., Bell, G. R., and Wirsig, O. A. (1972), "Chemical-Physical Treatment of Municipal Wastewater Using Continuous Counter-current Filtration," Journal of the Water Pollution Control Federation, Volume 44, Number 4, pp. 574-582.

58. Lin, A. C. Y. (1975), Simulation Model for Settling Basin Analyses, Ph.D. Thesis, Northwestern University, Evanston, Illinois.

59. Lynam, B. T., and Bacon, V. W. (1970), "Filtration and Micro-straining of Secondary Effluent," Water Quality Improvement by Physical and Chemical Processes, Water Resources Symposium Number 3, Center for Research in Water Resources, University of Texas Press, pp. 132-148.

60. Lynam, B., Ettelt, G., and McAloon, T. (1969), "Tertiary Treatment at Metro Chicago by Means of Rapid Sand Filtration and Micro-strainers," Journal of the Water Pollution Control Federation, Volume 41, Number 2, Part 1, pp. 247-279.

61. Mackrle, V., Dracka, O., and Svec, J. (1965), Hydrodynamics of the Disposal of Low Level Liquid Radioactive Wastes in Soil, International Atomic Energy Agency, Contract Report 98.

62. Mallet, C. H., and Pacquant, J. (1954), Erdstaudamme, Veb Verlag Technik, Berlin, Germany.

63. Maroudas, A., and Eisenklam, P. (1965), "Clarification of Suspensions: A Study of Particle Deposition in Granular Media, Part II: A Theory of Clarification," Chemical Engineering Science, Volume 20, Number 10, pp. 875-888.

64. McCluney, W. R. (1975), "Radiometry of Water Turbidity Measurements," Journal of the Water Pollution Control Federation, Volume 47, Number 2, pp. 252-266.

65. Mintz, D. M., and Krishtul, V. P. (1960), "Investigation of a Suspension in a Granular Bed," Journal of Applied Chemistry (English Translation), Volume 33, Number 2, pp. 303-314.

66. Monroe, D. W., and Pelmulder, J. P. (1973), "Wastewater Solids Reduction Using the Sonic Strainer Micro Screen," Paper presented at the Water and Wastewater Equipment Manufacturers Convention, Chicago, Illinois.

67. Monsanto Company (1974), Comparative Laboratory Evaluation of Plastic Filter Cloths, Unpublished Report, St. Louis, Missouri.

68. Moulik, S. P. (1971), "Physical Aspects of Electrofiltration," Environmental Science and Technology, Volume 5, Number 9, pp. 771-776.

69. Murphy, W. L., and Zeigler, T. W. (1974), Practice and Problems in the Confinement of Dredged Materials in Corps of Engineers Projects, Technical Report D-74-2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

70. National Oceanic and Atmospheric Administration - National Oceanographic Instrumentation Center (1974), Conclusions and Recommendations, Turbidity Workshop, Arlington, Virginia.

71. Rushton, A. (1972a), "Role of the Cloth in Filtration," Filtration and Separation, Volume 9, Number 1, pp. 81-88.

72. Rushton, A. (1972b), "Size and Concentration Effects in Filter Cloth Pore Bridging," Filtration and Separation, Volume 9, Number 3, pp. 274-278.

73. Shekhtman, Y. M. (1961), Filtration of Suspended Matter of Low Concentration, Treatise to Institute of Mechanics, Academy of Science, Moscow, USSR.

74. Silveira, A. (1965), "Analysis of the Problem of Washing through in Protective Filters," Proceedings of the Sixth International Conference on Soil Mechanics and Foundation Engineering, Montreal, Volume 2, Paper 6/27, pp. 551-555.

75. Smith, C. V. (1967), "Determination of Zeta Potential," Journal of the Sanitary Engineering Division, American Society of Civil Engineers, Volume 93, Number SA5, pp. 91-107.

76. Smith, J. W., Scott, H. A., and MacInnes, D. A. (1973), "The Theory and Practice of Upflow Sand Filtration," Filtration Engineering, Volume 4, Number 6, pp. 14-17.

77. Steimle, S. E., and Haney, B. J. (1974), "Potable Water Supply by Means of Upflow Filtration (L'Eau Claire Process)," Journal of the American Water Works Association, Volume 66, Number 2, pp. 117-123.

78. Sybron Corporation (1972), Automatic Valveless Gravity Filter, Bulletin Number 4351-F, Paramus, New Jersey.

79. Terzaghi, K. (1922), "Der Grundbruch an Stauwerken und seine Verhütung," Die Wasser-Kraft, Volume 17, pp. 445-449.

80. Terzaghi, K., and Peck, R. B. (1967), Soil Mechanics in Engineering Practice, John Wiley & Sons, Inc., New York, New York.

81. Tiller, F. M. (1972), Theory and Practice of Solid-Liquid Separation, Chemical Engineering Department, University of Houston, Houston, Texas.

82. Tiller, F. M. (1974), "Bench Scale Design of SLS Systems," Chemical Engineering, Volume 81, Number 9, pp. 117-119.

83. Tiller, F. M., Wilensky, J., and Farrell, P. J. (1974), "Pretreatment of Slurries," Chemical Engineering, Volume 81, Number 9, pp. 123-126.

84. Trzaska, A. (1966), "Colmatage Phenomena in an Artificial Porous Medium," Zezyty Problemowe Gornictwa PAN, Volume 4, Number 2, pp. 257-293.

85. Trzaska, A. (1972), "New Kinetics Equations of the Colmatage Process and their Applications," Archiwum Gornictwa, Volume 17, Number 4, pp. 361-384.

86. U.S. Army Corps of Engineers, Buffalo District (1969), Dredging and Water Quality Problems in the Great Lakes, Twelve-volume Technical Report, Buffalo, New York.

87. U.S. Army Corps of Engineers, Chicago District (1972), Letter Report on Confined Disposal Areas for Milwaukee and Port Washington Harbors, Wisconsin, Chicago, Illinois.

88. U.S. Army Corps of Engineers, New Orleans District (1973), Dredge Spoil Criteria in the New Orleans District, New Orleans, Louisiana.

89. U.S. Army Corps of Engineers, Philadelphia District (1969), Long Range Spoil Disposal Study, Six-volume Technical Report, Philadelphia, Pennsylvania.

90. U.S. Army Corps of Engineers, Providence District (1942), Filter Design-Tentative Design Procedure, Providence, Rhode Island.

91. U.S. Army Corps of Engineers, Sacramento District (1974), Water Quality Report; Walnut Creek Channel Dredging, Office Report, Sacramento, California.

92. U.S. Army Corps of Engineers, South Pacific Division (1972), Tests for Pollutants in Water Samples; Benecia Bridge, Stockton Port, Stockton Channel and Calaveras River, Final Report, Corps of Engineers Laboratory, Sausalito, California.

93. U.S. Army Corps of Engineers, South Pacific Division (1973), Analysis of Samples from Dredging of Sacramento Deep Water Ship Channel, Corps of Engineers Laboratory, Sausalito, California.

94. U.S. Army Corps of Engineers, Waterways Experiment Station (1941), Investigation of Filter Requirements for Under-Drains, Technical Memorandum Number 183.1, Vicksburg, Mississippi.

95. U.S. Army Corps of Engineers, Waterways Experiment Station (1948), Laboratory Investigation of Filters for Emid and Granada Dams, Technical Memorandum 3-150, Vicksburg, Mississippi.

96. U.S. Army Corps of Engineers, Waterways Experiment Station (1953), Filter Experiments and Design Criteria, Technical Memorandum 3-360, Vicksburg, Mississippi.

97. Water and Water Engineering (1968), "The Simater Continuous Sand Filter," Volume 72, Number 863, pp. 20-21.

98. Weber, W. J., Jr. (1972), Physicochemical Processes for Water Quality Control, Wiley-Interscience, John Wiley & Sons, Inc., New York, New York.

99. Westinghouse (1971), Squeegee Capillary Sludge Dewatering Unit, Descriptive Bulletin 81-840, Richmond, Virginia.

100. Wright, A. M., Kavanaugh, M. C., and Pearson, E. A. (1970), Filtration Kinetics in Water and Waste Water, First Annual Progress Report, by the University of California to the Environmental Protection Agency, EPA Grant 17030-ECA, Berkeley, California.

101. Yao, K. M. (1975), "Extended Plain Sedimentation," Journal of the Environmental Engineering Division, American Society of Civil Engineers, Volume 101, Number EE3, pp. 413-423.

102. Zurn Industries, Inc. (1971), Verti-Matic Up-flow Filtration System, Descriptive Bulletin, Erie, Pennsylvania.

APPENDIX A: PHYSICAL AND CHEMICAL DATA FOR BOTTOM SEDIMENTS

1. The information presented in this appendix was extracted from the literature, unpublished reports, and files of Corps of Engineer District offices, and it comprises part of a background study aimed toward characterizing dredged material and disposal area effluents. An effort was made to collect information from all geographic regions of the country so that a realistic picture of the chemical constituents and grain-size distributions could be obtained for bottom sediments that are candidates for dredging.

2. The pre-1975 EPA regulatory criteria for open water disposal of dredged material (now superseded) specified limits for seven chemical parameters. Therefore, for the vast majority of sampled bottom sediments, values for only these parameters were obtained; these data are listed in Table A1 and given as frequency distributions in Figure A1

3. The average grain-size distribution was obtained for bottom sediment from 60 locations around the country, and these data are presented in Table A2; the portions of grains smaller than 100, 10, and 1μ are presented as frequency distributions in Figure A2.

Table A1

Chemical Constituents of Bottom Sediments

District	Location and Number of Samples	Volatile Solids	Chemical Oxygen Demand	Total Kjeldahl Nitrogen	Oil and Grease	Mercury	Lead	Zinc
		Chemical Constituent (percent on a dry weight basis)						
San Francisco	Crescent City Harbor (3 samples)	—	—	—	0.13 0.25 0.31	0.000050 0.000057 0.000060	0.0008 0.0009 0.0010	0.0050 0.0058 0.0065
San Francisco	Noyo Harbor (6 samples)	2.1 6.8 22.5	0.5 7.5 32.7	0.02 0.10 0.35	0.01 0.06 0.22	0.000010 0.000020 0.000070	0.0011 0.0014 0.0018	0.0036 0.0063 0.0084
San Francisco	San Francisco Harbor (4 samples)	—	0.5 1.3 2.6	0.01 0.03 0.06	0.09 0.25 0.84	0.000001 0.000015 0.000056	0.0012 0.0036 0.0058	0.0035 0.0068 0.0106
San Francisco	Petaluma River (16 samples)	—	—	—	0.03 0.14 0.78	0.000020 0.000058 0.000090	0.0018 0.0043 0.0057	0.0034 0.0109 0.0149
San Francisco	Santa Cruz Harbor (2 samples)	—	0.1 0.1 0.2	0.01 0.01 0.01	—	0.000019 0.000024 0.000028	0.0007 0.0007 0.0007	0.0022 0.0024 0.0026
San Francisco	Richmond Harbor (13 samples)	3.8 6.6 8.3	2.6 4.1 5.0	0.07 0.13 0.18	0.01 0.08 0.34	0.000010 0.000053 0.000100	0.0006 0.0031 0.0050	0.0658 0.0134 0.0219
San Francisco	Oakland Harbor (5 samples)	2.1 4.1 7.9	0.9 3.2 6.1	0.02 0.08 0.13	0.03 0.14 0.43	0.000010 0.000066 0.000220	0.0014 0.0070 0.0136	0.0041 0.0142 0.0274
San Francisco	Alameda Naval Air Station (39 samples)	0.9 6.5 12.0	0.8 4.2 8.7	0.01 0.13 0.32	0.01 0.15 0.55	0.000008 0.000063 0.000140	0.0006 0.0056 0.0150	0.0016 0.0118 0.0380
San Francisco	Suisun Bay (7 samples)	1.1 2.9 6.9	0.3 2.0 5.5	0.01 0.06 0.18	0.01 0.02 0.03	0.000001 0.000010 0.000020	0.0010 0.0014 0.0022	0.0045 0.0058 0.0085
San Francisco	Redwood City (16 samples)	0.8 6.1 8.0	0.8 4.6 9.4	0.01 0.02 0.04	0.01 0.07 0.16	0.000012 0.000031 0.000065	0.0028 0.0099 0.0286	0.0089 0.0190 0.0343
San Francisco	Pinole Shoal (2 samples)	—	—	—	0.14 0.45 0.77	0.000005 0.000021 0.000036	0.0022 0.0025 0.0029	0.0068 0.0071 0.0074
San Francisco	Moss Landing (7 samples)	2.8 5.7 8.2	1.6 3.8 5.6	0.06 0.13 0.20	0.02 0.08 0.20	0.000007 0.000040 0.000095	0.0006 0.0028 0.0055	0.0020 0.0071 0.0122
San Francisco	John Baldwin Ship Channel (104 samples)	1.7 5.2 9.3	0.4 3.6 13.8	0.01 0.09 0.23	0.01 0.05 0.18	0.000010 0.000031 0.000400	0.0009 0.0024 0.0066	0.0039 0.0078 0.0218
Sacramento	Stockton Deep Water Channel (38 samples)	1.0 6.0 21.0	0.3 5.0 30.0	0.01 0.10 0.36	0.01 0.03 0.23	0.000001 0.000006 0.000031	0.0005 0.0022 0.0030	0.0021 0.0077 0.0102
Los Angeles	San Diego Harbor (144 samples)	0.7 4.2 11.1	0.08 2.9 10.8	0.01 0.08 0.40	0.01 0.11 0.49	0.000003 0.000042 0.000180	0.0001 0.0033 0.0192	0.0010 0.0105 0.0421
Seattle	Tacoma Harbor (8 samples)	0.8 2.2 5.2	0.7 3.0 6.4	0.01 0.04 0.09	0.03 0.10 0.30	—	0.0010 0.0025 0.0070	0.0020 0.0075 0.0070
Seattle	Willapa Harbor (10 samples)	4.7 9.8 15.7	2.9 8.6 16.5	0 0.16 0.31	0.04 0.10 0.15	—	0.0030 0.0040 0.0050	0.0200 0.0270 0.0370
Seattle	Grays Harbor and Chevalis River (14 samples)	2.5 6.9 10.2	1.8 6.7 10.2	0.02 0.08 0.17	0.02 0.07 0.12	—	0.0002 0.0015 0.0042	0.0050 0.0070 0.0080
Seattle	Duwamish Waterway (13 samples)	1.4 7.3 11.6	0.3 6.0 10.0	0.02 0.12 0.24	0.04 0.16 0.33	0.000003 0.000010 0.000021	0.0007 0.0024 0.0059	0.0081 0.0136 0.0201
Seattle	Kingston Harbor (2 samples)	1.6 1.7 1.8	1.3 1.5 1.7	0.04 0.04 0.04	0.17 0.22 0.26	—	0 0.0005 0.0010	0.0030 0.0030 0.0030
Seattle	Port Townsend (2 samples)	1.5 2.7 3.8	2.2 3.2 4.2	0.05 0.07 0.10	0.04 0.19 0.33	—	0.0030 0.0040 0.0050	0.0030 0.0040 0.0050
Seattle	Swinomish Channel (3 samples)	1.3 1.3 1.4	0.4 0.5 0.6	0.012 0.015 0.019	0.02 0.04 0.05	—	0.0010 0.0010 0.0010	0.0010 0.0030 0.0050
Seattle	Everett, Washington Harbor (9 samples)	1.4 2.5 5.4	0.3 1.0 4.7	0.01 0.03 0.08	0 0.03 0.08	—	0 0.0009 0.0020	0.0027 0.0041 0.0060
Galveston	Corpus Christi Ship Channel (11 samples)	8.3 9.7 11.0	1.4 2.1 2.8	0.48 0.85 1.30	0.09 0.10 0.11	0.000038 0.000071 0.000140	0.0087 0.0157 0.0330	0.0097 0.0253 0.0480
New Orleans	Breton Sound (6 samples)	1.5 4.8 5.9	1.9 4.2 6.6	0.06 0.13 0.16	0.01 0.10 0.18	0.000010 0.000010 0.000010	0.0001 0.0017 0.0035	0.0049 0.0072 0.0110

(continued)

Table A1 (Concluded)

District	Location and Number of Samples	Chemical Constituent (percent on a dry weight basis)						
		Volatile Solids	Chemical Oxygen Demand	Total Kjeldahl Nitrogen	Oil and Grease	Mercury	Lead	Zinc
New Orleans	Bayou Barataria Perot, Louisiana (12 samples)	4.2 10.2 26.0	1.8 12.3 42.5	0.06 0.36 0.89	0.01 0.04 0.12	0.000005 0.000030 0.000084	0.0007 0.0013 0.0023	0.0095 0.0147 0.0226
New Orleans	Calcasieu River at Coon Island (6 samples)	4.1 10.0 21.0	4.1 11.0 26.9	0.07 0.16 0.26	0.03 0.44 1.97	0.000042 0.000105 0.000220	0.0002 0.0002 0.0002	0.0021 0.0176 0.0764
New Orleans	Calcasieu Ship Channel (5 samples)	3.7 5.2 6.5	1.8 2.9 3.8	0.04 0.08 0.11	0.02 0.04 0.08	0.000010 0.000020 0.000060	0.0001 0.0007 0.0012	0.0064 0.0155 0.0150
New Orleans	Mississippi River Southwest Pass (7 samples)	1.9 4.0 5.1	0.7 2.0 3.5	0.02 0.07 0.09	0.01 0.04 0.06	0.000010 0.000015 0.000040	0.0001 0.0010 0.0020	0.0047 0.0075 0.0121
New Orleans	Mississippi River South Pass (7 samples)	2.6 4.4 5.8	1.3 3.2 6.7	0.01 0.06 0.11	0.01 0.02 0.03	0 0.000005 0.000010	0.0001 0.0006 0.0015	0.0025 0.0050 0.0084
New Orleans	Mississippi River at New Orleans (4 samples)	0.9 2.0 4.3	0.2 1.3 2.2	0.03 0.05 0.07	0.01 0.04 0.09	0.000001 0.000008 0.000020	0.0010 0.0018 0.0043	0.0040 0.0048 0.0060
New Orleans	Mississippi River Gulf Outlet (3 samples)	2.6 2.7 2.8	2.9 3.1 3.6	0.13 0.18 0.23	0.04 0.05 0.05	0.000009 0.000011 0.000014	0.0001 0.0001 0.0002	0.0036 0.0038 0.0039
New Orleans	Bayou Petit Anse and Carlin (5 samples)	3.9 6.2 10.9	1.7 6.7 17.7	0.05 0.15 0.32	0.02 0.03 0.05	0.000005 0.000008 0.000012	0 0 0	0.0041 0.0060 0.0104
Jacksonville	Mayport Carrier Basin (2 samples)	11.3 14.2 17.2	8.4 11.4 14.3	0.26 0.37 0.48	0.15 0.19 0.22	0.000220 0.000270 0.000310	0.0164 0.0192 0.0220	0.0085 0.0168 0.0250
Savannah	Brunswick Harbor and Estuary (13 samples)	0.8 8.3 17.2	0.1 6.0 12.5	0.01 0.19 0.44	0.02 0.20 0.40	0.000010 0.000070 0.000210	0.0005 0.0011 0.0028	0.0005 0.0099 0.0388
Norfolk	Burtons Bay (3 samples)	4.9 5.0 5.3	4.9 5.6 6.2	0.11 0.12 0.15	0.01 0.02 0.03	0.000008 0.000010 0.000012	—	0.0055 0.0062 0.0069
Norfolk	Swash Bay (3 samples)	5.4 5.8 6.3	6.8 7.6 8.2	0.16 0.18 0.20	0.05 0.07 0.09	0.000009 0.000010 0.000010	—	0.0023 0.0025 0.0028
Norfolk	Sloop Channel (3 samples)	3.5 4.8 5.7	4.0 5.5 6.5	0.09 0.11 0.14	0.07 0.09 0.11	0.000004 0.000005 0.000006	—	0.0043 0.0055 0.0063
Norfolk	Rirker Creek (4 samples)	3.6 4.9 5.8	—	0.15 0.30 0.56	0.03 0.05 0.08	0.000001 0.000005 0.000009	—	0.0052 0.0063 0.0072
Norfolk	Stallings (5 samples)	5.2 8.4 10.6	—	0.26 0.32 0.39	0.01 0.14 0.34	0.000001 0.000005 0.000009	—	0.0052 0.0079 0.0104
Buffalo	Buffalo Harbor and River (14 samples)	6.8 9.6 12.6	6.5 12.6 21.8	0.18 0.23 0.32	0.17 0.83 1.05	—	—	—
Buffalo	Cleveland Harbor (20 samples)	4.1 6.2 10.5	5.0 9.0 15.0	0.01 0.18 0.30	0.22 0.65 0.95	—	—	—
Buffalo	Great Sodus Bay (15 samples)	0.5 4.7 9.6	0.1 1.1 3.2	0.04 0.25 0.42	0.02 0.25 0.82	—	—	—
Chicago	Indiana Harbor (10 samples)	6.6	26.1	0.23	2.79	—	0.0396	0.1480
Chicago	Calumet Harbor (7 samples)	4.4 7.7 13.2	6.9 13.9 23.1	0.07 0.10 0.12	0.34 1.48 3.44	—	0.0079 0.0337 0.0820	0.0039 0.0226 0.0472
Chicago	Green Bay Harbor (12 samples)	1.8 4.6 7.2	5.0 15.2 30.0	0.14 0.69 1.01	0.46 1.35 4.60	—	—	—
Chicago	Milwaukee Harbor (3 samples)	9.2 15.0 24.1	7.2	—	1.10 7.00 16.90	—	0.0191 0.0712 0.1413	—
Detroit	Rouge River (26 samples)	6.0 16.2 35.0	—	—	0.10 1.69 6.00	—	0.0081	—
Detroit	Toledo Harbor (12 samples)	8.9 10.2 17.3	7.9 10.7 18.4	—	0.08 0.59 1.48	—	0.0070 0.0111 0.0160	—

Table A2

Grain-Size Distributions of Bottom Sediments

District	Location	Percent finer than (by weight) in mm							
		5	1	0.5	0.1	0.05	0.01	0.005	0.001
San Francisco	San Francisco	100	99	97	67	48	30	26	14
San Francisco	Redwood City	100	99	97	96	85	55	32	12
San Francisco	Oakland	—	—	100	99	97	70	55	31
San Francisco	Richmond	—	—	100	92	82	51	42	25
San Francisco	San Rafael	—	—	100	98	82	48	37	21
San Francisco	Pinole Shoal	—	100	99	60	52	39	31	20
San Francisco	Mare Island	—	—	100	99	90	54	43	23
San Francisco	Suisun Bay	—	100	99	53	43	33	27	17
San Francisco	Napa River	99	97	96	68	58	37	30	18
San Francisco	Petaluma Creek	—	—	100	99	90	65	54	30
Seattle	Kingston Harbor	100	99	98	55	35	7	5	3
Seattle	Olympia Harbor	100	99	98	90	86	74	58	28
Seattle	Port Townsend	87	82	80	30	20	10	7	2
Seattle	Quillayute River	—	—	100	50	30	8	7	5
Seattle	Duwamish	100	91	88	62	44	19	13	9
Seattle	Skagit Bay	100	98	95	80	73	38	23	10
Seattle	Hylebos	98	96	94	86	82	48	26	13
Seattle	Willapa River	—	100	99	98	96	55	30	7
Seattle	Grays Harbor	—	100	99	86	71	36	22	10
Seattle	Anacortes Harbor	—	100	99	98	96	55	30	17
Sacramento	Stockton Channel	100	98	96	78	66	40	30	16
Los Angeles	Port Hueneme	100	98	96	55	35	16	10	5
Los Angeles	San Diego	100	98	95	62	56	38	30	19
Baltimore	Graighill (1)	—	—	—	—	100	78	59	26
Baltimore	Graighill (2)	—	—	—	—	100	74	60	29
Baltimore	Braverton (1)	—	—	—	—	100	85	66	33
Baltimore	Braverton (2)	—	—	—	—	100	80	67	23
Norfolk	Swash Bay	—	—	—	100	99	65	31	10
Norfolk	Sloop Channel	—	—	—	100	99	65	36	10
Norfolk	Burtons Bay	—	—	—	100	99	66	38	10

(Continued)

Table A2 (Concluded)

District	Location	Percent finer than (by weight) in mm							
		5	1	0.5	0.1	0.05	0.01	0.005	0.001
Wilmington	Surry Point	—	—	—	100	97	72	56	49
Charleston	General	—	100	99	70	65	55	50	36
Jacksonville	Mayport (1)	—	—	100	94	90	79	73	35
Jacksonville	Mayport (2)	—	—	100	82	72	56	48	26
Philadelphia	Edgmoor	—	—	100	90	80	59	46	27
Philadelphia	Darby Creek	—	100	99	82	70	53	43	25
Philadelphia	Oldsmans	—	—	100	98	93	70	55	33
Philadelphia	Pigeon Point	—	100	99	90	70	50	42	29
New York	General	98	88	74	41	32	15	10	5
New Orleans	Calcasieu River	—	—	—	100	97	73	61	34
Galveston	Sabine Bar	—	—	100	98	94	79	70	49
Galveston	Sabine Bank	99	98	97	81	70	49	42	31
Galveston	Sabine Neckes	—	—	100	93	84	67	59	35
Galveston	Galveston Harbor	—	100	99	90	68	56	49	31
Galveston	Freeport Harbor	—	—	100	94	70	48	38	28
Galveston	Matagorda	85	78	77	67	48	42	39	25
Galveston	Corpus Christi	98	95	94	79	44	31	27	18
Chicago	Calumet Harbor	100	98	97	86	78	49	35	18
Chicago	Indiana Harbor	100	95	86	73	66	32	20	10
Chicago	Green Bay Harbor	100	95	87	75	67	50	42	27
Buffalo	Buffalo Harbor	100	98	96	86	78	30	15	8
Buffalo	Cleveland Harbor	100	98	96	85	76	40	20	10
Buffalo	Great Sodus Harbor	100	95	80	55	45	22	13	7
Detroit	Rouge River	100	90	81	61	52	31	23	15
Detroit	Toledo Harbor	100	99	98	92	85	63	45	23
Detroit	Maumee River	100	97	92	90	80	53	42	20
Detroit	Monroe	100	99	94	89	77	42	26	12
Detroit	Saginaw	—	100	99	91	79	40	23	10
Detroit	West Sailing Course	—	100	99	97	84	49	32	21
Detroit	Maumee Bay	—	100	96	77	63	51	36	19

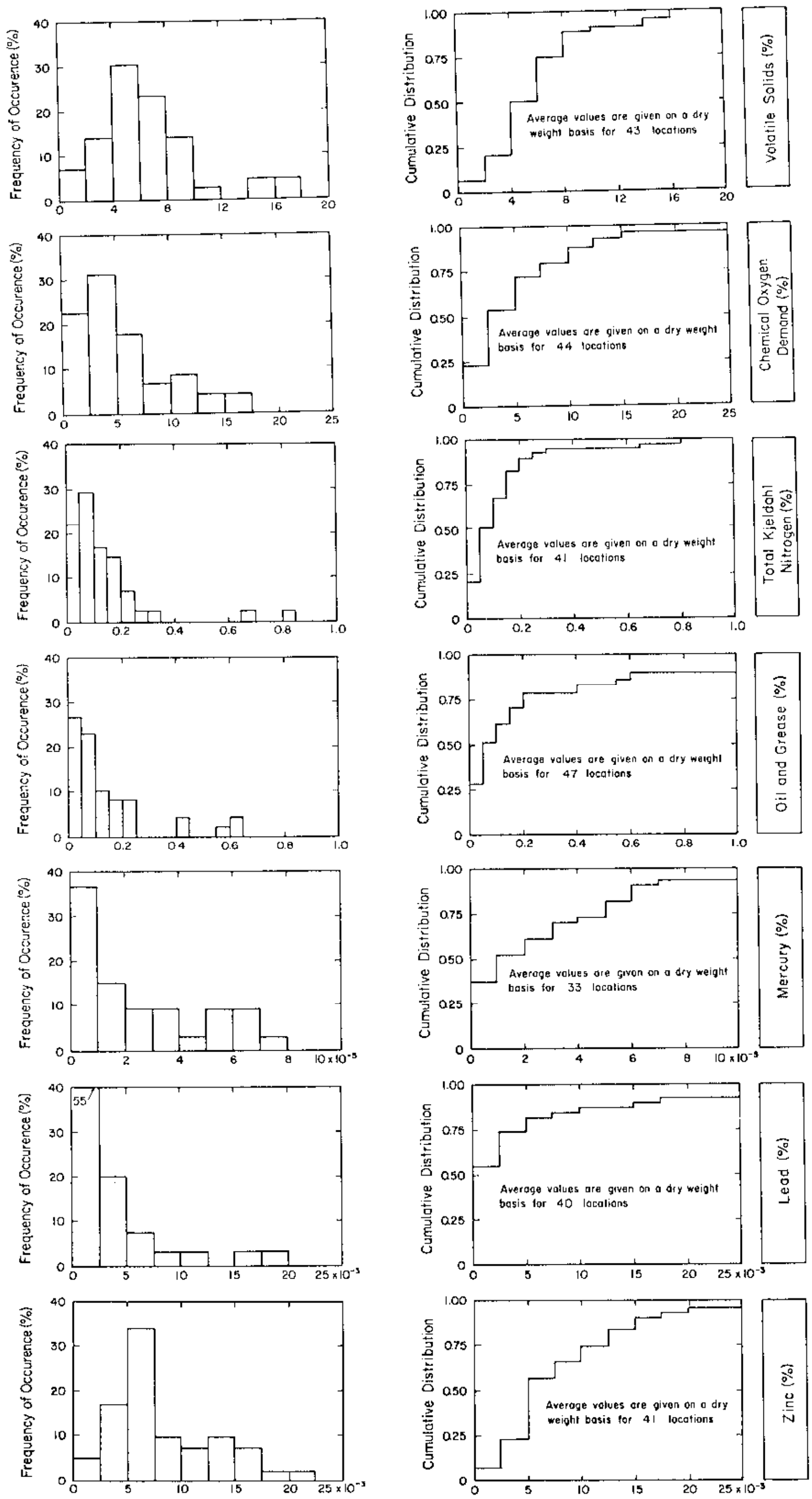

Figure A1. Statistical Distributions of Chemical Constituents in Bottom Sediments

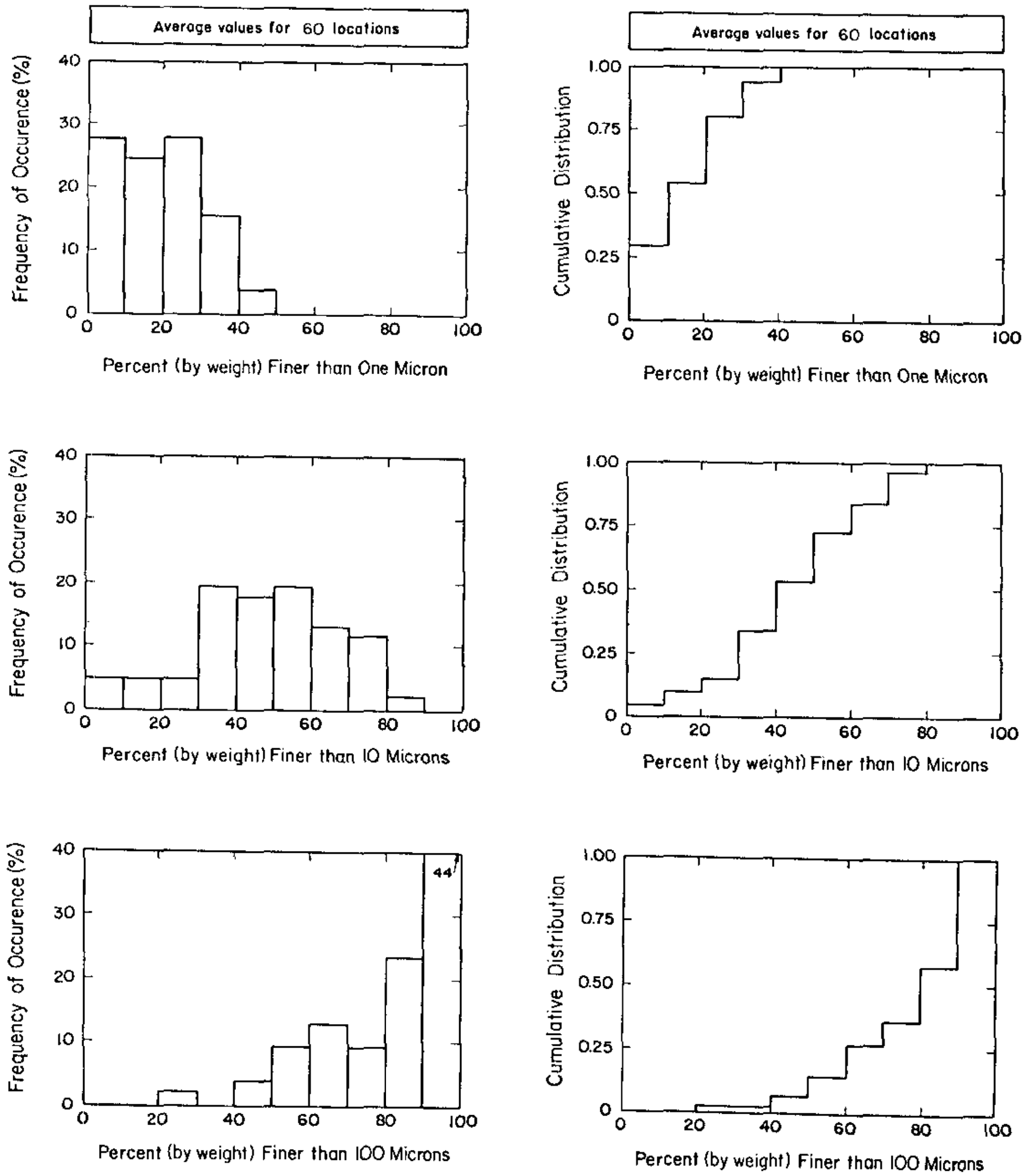

Figure A2. Statistical Distributions of Grain-Size Data for Bottom Sediments

APPENDIX B: CORRELATION BETWEEN TURBIDITY AND MASS CONCENTRATION

1. The turbidity of a sample is a measure of the interference presented by suspended matter to the passage of light (Fair and Geyer, 1966). However, turbidity is not directly equivalent to the amount of suspended matter, since the interference is a function of the size, shape, number, and index of refraction of the suspended particles. Considerable background work (NOAA/NOIC Turbidity Workshop, 1974; McCluney, 1975) has indicated that (a) turbidity is strictly an optical property of the medium; (b) the use of the term "turbidity" is ambiguous; (c) instrument calibration may be misleading and incorrect; (d) optical instruments in current use provide an inferred and not a direct measurement of suspended solids; (e) the use of turbidimeters must be supported by ancillary measurements which demonstrate that the optical data are correlated with the concentrations of the materials to be monitored; and (f) a transfer function, not a single-point calibration, is required to convert optical readings from a given instrument to actual mass concentrations of suspended solids. In spite of these difficulties, many investigators have attempted to establish a relation between turbidity and concentration of suspended particles for very specific sets of conditions.

2. Turbidimetry has the advantage of being a speedy process; whereas the direct methods of mass concentration determination (i.e. gravimetry) are time consuming. In this study an effort was made to develop a correlation between turbidity, mass concentration, and suspended particle size distribution for the artificial suspensions used in conducting the experimental program of laboratory filtration tests reported herein. Described in the following paragraphs are (a) the method used to obtain the necessary data, (b) the actual data, and (c) the conclusions drawn.

3. The following procedures were employed to obtain data for suspensions of Grundite and kaolinite in fresh (tap) water:

- a. A Waring blender was used to thoroughly mix 10 g of solids with 1 ℓ of water.

b. The suspension was transferred to a standard graduated cylinder, such as used for hydrometer analyses, and allowed to settle for a specified period of time.

c. The top 200 ml of the suspension were carefully siphoned into a clean beaker.

d. The mass concentration of suspended solids was obtained by gravimetry for 100 ml of each sample.

e. The grain-size distribution of the suspended solids in each sample was obtained by use of a Model A Coulter Counter.

f. The turbidity of each sample was obtained by means of a Hach 1860 laboratory turbidimeter, and the turbidities of consecutive dilutions of the sample in fresh water were then determined.

4. Figures B1 and B2 show the turbidity readings plotted versus the mass concentration values for samples collected at different settling times. Tables B1, B2, B3 and B4 summarize the information on the grain size distributions, mass concentrations, and numbers of suspended particles. All particle counts were obtained for the suspension volume processed by the Coulter Counter (0.8 ml). Since the detection of particle sizes smaller than 1.1μ requires the use of considerably more complicated techniques that can introduce greater inaccuracies, it is not necessarily correct to conclude that the lower limit of particle sizes in the suspensions was 1.1μ. Based on the available data, the following observations were made for the Grundite and kaolinite suspensions:

a. The grain-size distribution of the suspended particles does not change significantly as the settling time increases.

b. Settling drastically reduces the number of suspended particles and therefore the mass concentration of the suspended solids.

c. Small changes in the grain-size distribution and drastic reductions in the number of suspended particles do not significantly affect the turbidity readings for the same mass concentration.

5. Within the scope and limitations of these data and observations, the following conclusions can be advanced with respect to the specific Grundite and kaolinite suspensions used throughout the

laboratory experimental program:

a. For all practical purposes, the relationship between turbidity and mass concentration of suspended solids is independent of the grain-size distribution.

b. For a given mass concentration, the presence of a small amount of coarse suspended particles does not affect the turbidity reading.

c. The following relationships can be used to estimate the mass concentration, C, of a sample from its turbidity, T:

Grundite:	$\log C = 1.26 \log T - 0.32$	$(T < 100)$
	$\log C = 1.85 \log T - 1.50$	$(T > 100)$
Kaolinite:	$\log C = 1.22 \log T - 0.58$	$(T < 200)$
	$\log C = 3.18 \log T - 5.10$	$(T > 200)$

where the turbidity is expressed in JTU and the mass concentration is given in mg/ℓ.

Table B1

Grain-Size Distributions of Grundite Suspensions

Grain Size (microns)	Percent Finer (by number) Settling Time (minutes)				
	0	1	4	15	240
20	100.00	100.00	100.00	100.00	100.00
10	99.85	99.89	99.91	99.94	99.97
5	99.74	99.40	99.58	99.37	99.81
2	83.65	85.96	86.16	86.45	89.48
1.5	58.48	65.09	64.95	64.85	69.90
1.1	0	0	0	0	0

Table B2

Mass Concentration and Number of Particles for Grundite Suspensions

Settling Time (minutes)	Total Number of Particles	Mass Concentration (g/ℓ)
0	310,000	10.0
1	250,000	6.0
4	218,000	5.0
15	100,000	1.8
240	6,000	0.2

Table B3

Grain-Size Distributions of Kaolinite Suspensions

Grain Size (microns)	Percent Finer (by number)			
	Settline Time (minutes)			
	0	5	30	240
5.0	100.00	100.00	100.00	100.00
3.5	97.87	99.04	98.93	98.92
2.0	89.26	92.85	93.15	93.34
1.5	64.60	78.89	77.52	77.34
1.1	0	0	0	0

Table B4

Mass Concentration and Number of Particles for Kaolinite Suspensions

Settling Time (minutes)	Total Number of Particles	Mass Concentration (g/ℓ)
0	12,000	10.0
5	10,000	8.0
30	4,000	2.1
240	400	0.1

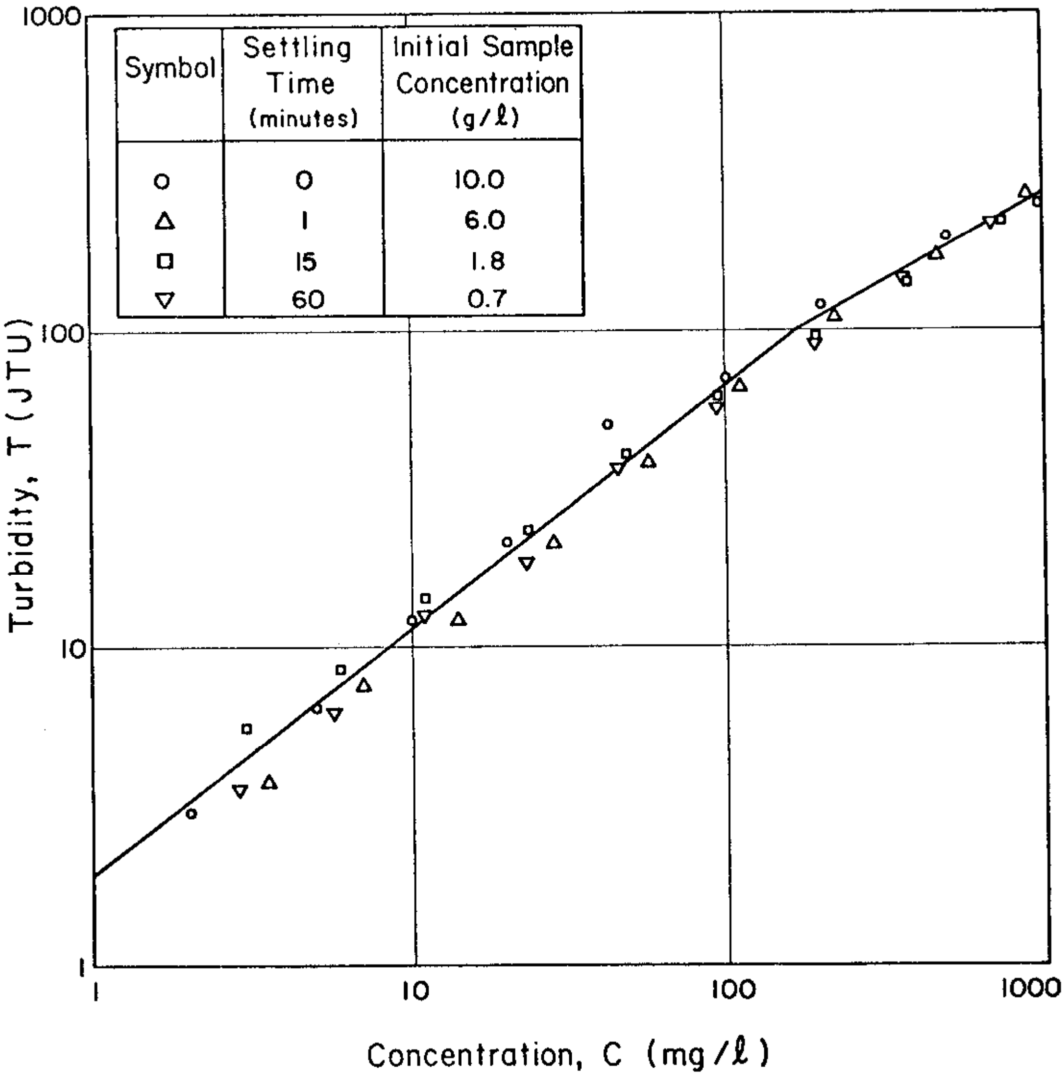

Figure B1. Turbidity versus Mass Concentration for Grundite Suspensions

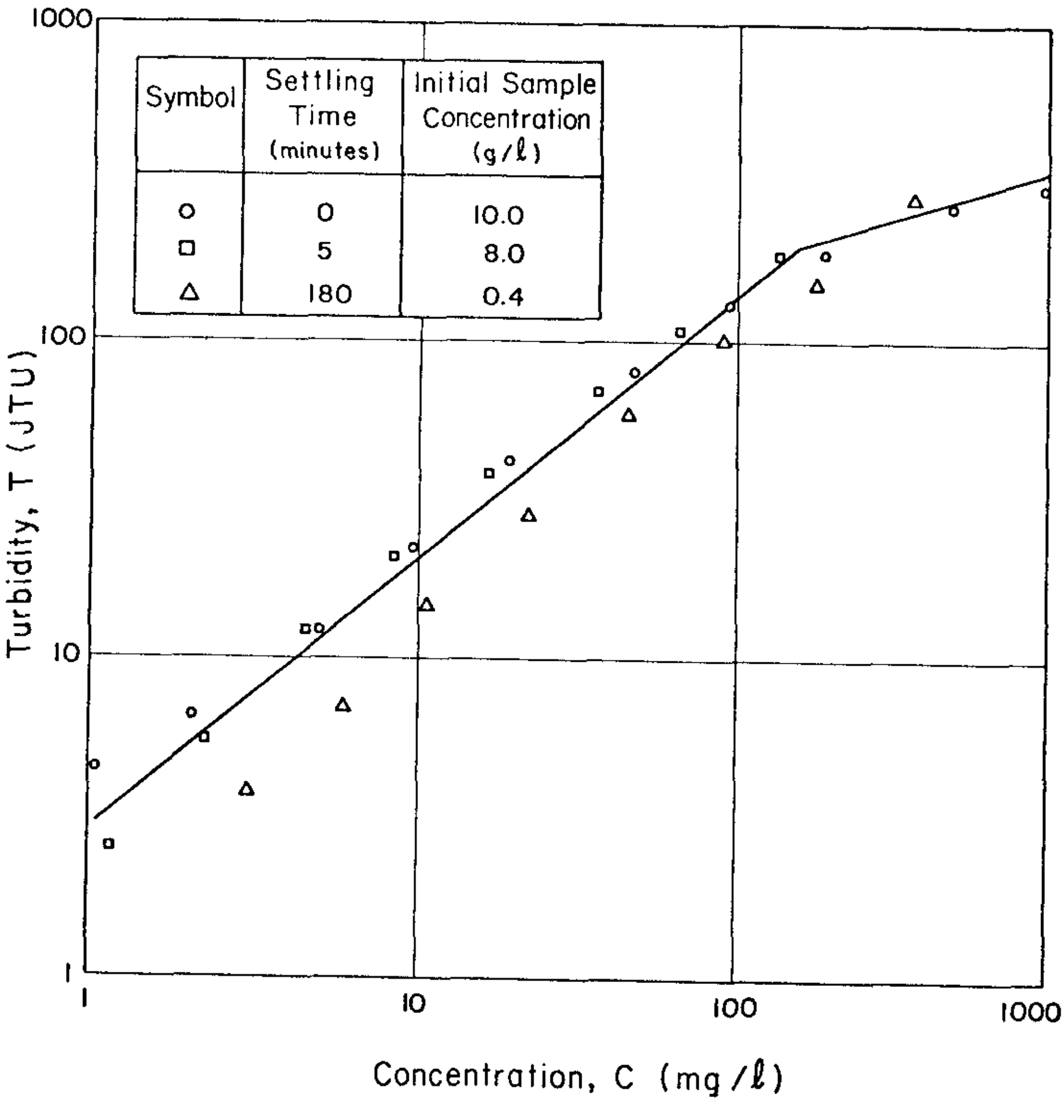

Figure B2. Turbidity versus Mass Concentration for Kaolinite Suspensions

APPENDIX C: VACUUM FILTRATION TESTS

1. From a technical point of view, vacuum filtration offers a possible solution to the problem of dewatering dredged material pumped into confined disposal areas. To obtain some insight into the filterability of dredged material slurries and the feasibility of using cake filtration equipment to dewater dredged material, a series of Buchner Funnel tests were conducted on a dredging sample from Cleveland, Ohio. Table C1 gives limited characterization data for the slurries tested, which were obtained by diluting the Cleveland sample with fresh water. The effect of chemical conditioning on the filterability of the slurries was investigated by adding ferric chloride ($FeCl_3 \cdot 6H_2O$) and/or lime ($Ca(OH)_2$) to the samples. The following procedure was used for conducting the tests:

- a. The filter paper was placed in the Buchner Funnel arrangement and then moistened to ensure a proper seal.
- b. Conditioning of the slurry was accomplished by adding the proper amounts of chemicals (ferric chloride prior to lime), as shown in Table C2.
- c. Approximately 100 ml of slurry were transferred to the Buchner Funnel, and gravity drainage was allowed for two minutes while the filtrate volume was recorded.
- d. At time equal zero, a 66 percent vacuum was applied, and the filtrate volume was recorded after predetermined gradually increasing time intervals starting with five seconds.
- e. Monitoring was continued until the vacuum was lost or until a maximum time of ten minutes was reached.
- f. The degree of adhesion of the cake on the filter paper was observed, and the cake was tested to determine its water content.
- g. The turbidity of the filtrate was obtained by use of a Hach 1860 laboratory turbidimeter.

2. The data collected during this brief investigation are presented in Table C2 and Figure C1. The specific resistance, r, was taken equal to $2bPA^2/\mu w$, where b reflects the relationship between the elapsed time and the volume of filtrate; P is the applied pressure difference;

A is the area of the funnel; μ is the absolute viscosity of water; and w is the weight of cake solids per unit volume of filtrate. Based on the data obtained, the following observations can be made:

- a. Aeration of the slurries did not significantly affect their specific resistance or the time required to collect a unit volume of filtrate.
- b. Conditioning with 4 percent or more ferric chloride reduced the specific resistance by a factor of 4. Conditioning with 4 and 8 percent lime reduced the specific resistance by a factor of 3 and 7, respectively. Conditioning with a combination of lime and ferric chloride did not reduce the specific resistance to levels lower than those obtained by the use of either chemical alone.
- c. The use of chemical conditioners reduced the filtration time by a factor of about 2, with little dependence on the amount of conditioner added.

3. Based on the data and observations described, the following conclusions can be advanced:

- a. Vacuum filtration is technically capable of dewatering dredged material slurries.
- b. Chemical conditioning with ferric chloride or lime can improve the filterability and rate of dewatering of dredged material slurries.
- c. The large volumes of dredged material to be handled may render the use of chemical conditioners economically unfeasible.
- d. A comprehensive experimental study is required to examine the feasibility of applying vacuum filtration techniques to dewater dredged material slurries.

Table C1

Characterization Data for Slurries Tested

Parameter	Nonaerated Samples	Aerated Samples
Total Solids	5.83	8.21
Total Suspended Solids	5.65	7.83
Total Volatile Solids	0.74	1.06
Total Suspended Volatile Solids	0.10	0.91
pH	7.2	7.4

Note: Solids contents are expressed in percent of wet weight.

Table C2

<u>Results of Vacuum Filtration Tests</u>

Sample Number	Ferric Chloride (% TS)	Lime (% TS)	Duration of Test (seconds)	Volume of Filtrate (ml)	Turbidity of Filtrate (JTU)	Water Content of Cake (%)	Adhesion of Cake to Filter Paper	Specific Resistance ($sec^2/gram \times 10^7$)
1	0	0	180	97	40	62.7	High	4.25
2	4	0	90	98	190	68.3	Low	1.13
3	8	0	80	104	170	75.6	Low	1.04
4	0	4	90	100	> 1000	66.6	High	1.35
5	4	4	125	97	195	77.2	High	3.48
6	8	4	100	104	300	77.2	Low	2.31
7	0	8	90	92	42	67.6	Low	0.62
8	4	8	90	100	150	74.9	Low	0.69
9	8	8	95	101	> 1000	83.5	Low	1.93
10	0	0	600	100	15	62.0	High	4.45
11	4	4	100	102	210	69.9	Low	1.80
12	8	8	110	106	230	88.3	Low	2.36

Notes:

1. Samples 10, 11, and 12 were aerated.
2. The cake did not crack for sample 10, and the test was terminated after 10 minutes.

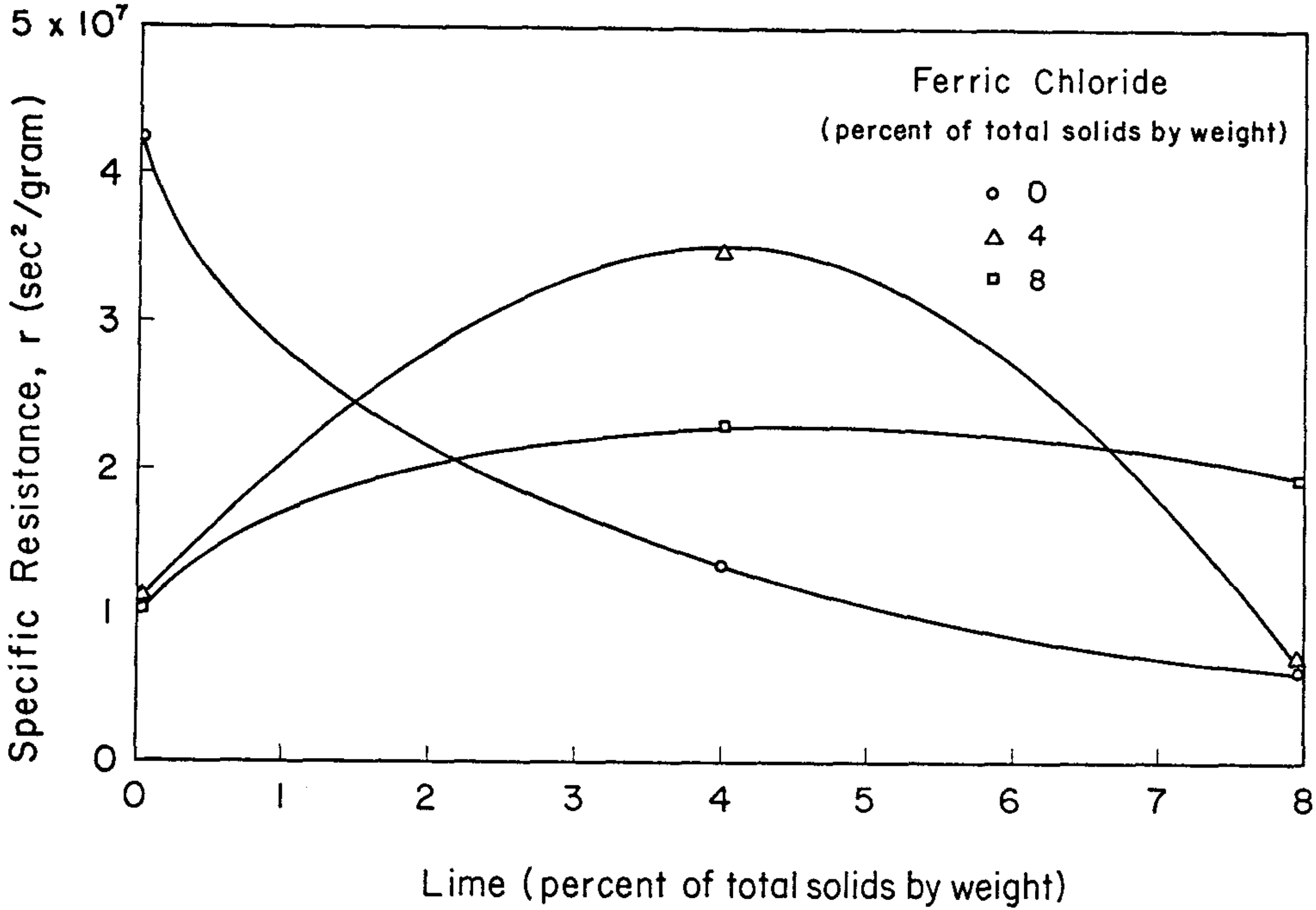

Figure C1. Specific Resistance versus Amount of Conditioner

APPENDIX D: SOLID-LIQUID SEPARATION TECHNOLOGY

1. The recognition of all possible alternative solutions, the evaluation of these solutions in terms of the specific problem to be addressed, and the selection of the best available technique are basic demands for good engineering practice. The rapid increase in solids-liquid separation alternatives in recent years has emphasized the modern philosophy that particle separation be treated as a system design, rather than simply the selection of a filter (Fitch, 1974; Tiller, 1974). In general, a solids-liquid separation system may consist of one or more of the following stages: (a) pretreatment (chemical coagulation-flocculation) to increase particle size; (b) solids concentration (thickeners and clarifiers); (c) solids separation by filters and centrifuges; and (d) posttreatment to remove solubles and reduce the moisture content of the final solids.

2. Pretreatment facilitates solids-liquid separation by increasing the particle size; consequently, it improves the sedimentation characteristics and/or produces less resistant filter cakes. This can be achieved by either chemical processes, such as coagulation and flocculation, or physical processes, such as crystallization, aging, freezing, and filteraid admix (Tiller, 1974). Gravity settling is generally effective for the separation of noncolloidal fines from waters and wastewaters, and it is the major method of solids concentration in clarifiers and thickeners (Fair and Geyer, 1966; Weber, 1972). Filter systems for solid-liquid separation fall into two classes; namely, those involving clarification and those dealing with separation via cake formation. Clarification, which is usually performed by means of deep-bed granular filters, cartridges, drum precoat clarifiers, filteraid admix filters, centrifuges, or hydrocyclones, involves removing of small quantities of solids that may be colloidal in nature and thereby circumventing the possibility of cake-type filtration. When cake filtration is indicated, the rate of cake-thickness growth is of primary importance in the selection of equipment, such as pressure, vacuum, or gravity filters, or solid or perforated-bowl centrifuges (Tiller, 1974).

In terms of operational characteristics, the various filter configurations can be categorized as mechanized and nonmechanized systems, and each category can be further subdivided into surface or depth filters, as described in Table 2. Posttreatment is accomplished by one of a number of techniques, such as washing, drying, and deliquoring, and it serves to provide end products that meet desired quality criteria and are in a condition appropriate for bulk handling and processing.

3. As explained in previous chapters, the major objective of this research was to develop and document a methodology for designing filter systems to control the concentrations of suspended solids in effluents from confinement disposal facilities for dredged material. However, the effectiveness of a given filter system cannot be evaluated without taking into account the characteristics of the confinement facility in which the design is incorporated; these characteristics are (a) the size and shape of the disposal area, (b) the relative locations of the inflow pipe and effluent filter system, and (c) the nature of the dredged material disposal operations. It is therefore both necessary and realistic to consider the combination of the disposal area and filters as a solids-liquid separation system which (a) can be activated, if necessary, when a dredged material slurry is pumped into the disposal area, (b) effectively retains the suspended solids, and (c) produces effluents of acceptable quality. Accordingly, solids-liquid separation systems are reviewed in this appendix with this perspective in mind, and emphasis is given to the application of such systems to the design of confinement facilities for dredged materials. Described in the following sections are (a) pretreatment of dredged material slurries by coagulation or flocculation, (b) sedimentation in disposal areas, and (c) various filter systems that could conceivably be incorporated in the design of a disposal area. The characteristics and performance capabilities of these systems are included, and attempts are made to provide first order approximations of capital investment requirements and operational and maintenance costs.

Chemical Pretreatment

4. The removal of a large proportion of the suspended impurities in water and wastewater treatment is accomplished by sedimentation. Many of these impurities exist as suspended particles that are too small and/or too near the specific gravity of water for gravitational settling alone to provide an effective removal process. Thus, the aggregation of these particles into larger, more readily settleable flocs is essential for successful and rapid separation by sedimentation. This result can be achieved by chemical pretreatment, known as coagulation or flocculation (Weber, 1972; Akers, 1975; Tiller, Wilensky, and Farrell, 1974).

5. The terms "coagulation" and "flocculation" are used in the literature indiscriminately to describe the coagulating effect of ions on hydrophobic colloids. La Mer (1964) suggested that the term "coagulation" be reserved for the effect brought about by reducing the zeta potential of a particle by changes in electrolyte concentration and that the term "flocculation" be reserved for the effect induced by long chain organic polymers that act by forming bridges between the solid particles; however, this terminology has not been universally accepted. In the following paragraphs, the term "flocculation" is used to describe the agglomeration of particles, irrespective of its mode of occurence.

6. Preconditioning agents include (a) starch, proteins, glue, gelatin, and other natural flocculating agents, (b) acids, bases, and salts of strong acids or weak bases that neutralize surface charges and allow the agglomeration of colliding particles due to van der Waals forces, and (c) high-molecular-weight polyelectrolytes that may destabilize particles by charge neutralization and promote flocculation by opposite charge attraction or bridging between particles.

7. A modest amount of information is available on the chemical pretreatment of dredged material slurries to increase flocculation and

improve the settleability of suspended solids. A study by the Galveston District of the U. S. Army Corps of Engineers (Murphy and Zeigler, 1974) resulted in the conclusions that (a) flocculation is practical only for dredged material slurries with a low solids content and (b) flocculation might be cost-effective as a clarification method to permit disposal area effluents to meet very strict quality standards.

8. The Dow Chemical Company (U. S. Army Corps of Engineers, Buffalo District, 1969) conducted a series of flocculation-sedimentation column tests on supernatants and effluents from two disposal areas in Toledo, Ohio. Dow reported the following:

- a. Treatment of disposal area effluents that contained about 1750 mg/ℓ of suspended solids with 2 to 10 mg/ℓ of Purifloc C-31 (organic polymer) resulted in supernatants with turbidities generally lower than 100 JTU.
- b. Similar results were obtained when 25 to 50 mg/ℓ hectorite clay or 5 to 100 mg/ℓ ferric chloride were used.
- c. The treatment of waters with suspended solids loads between 0.4 and 20 g/ℓ with 8 mg/ℓ of Purifloc C-31 resulted in turbidities ranging from 34 to 105 JTU.
- d. Water with high suspended solids loads (about 20 g/ℓ) was often easier to clarify than water with much lower concentrations (about 0.4 g/ℓ).
- e. The resulting floc sizes ranged from 100 to 700μ and had rapid settling velocities (0.05 cm/sec).
- f. At the rate of 8 mg/ℓ of Purifloc C-31, the cost of chemicals would be about \$5/1000 m^3 of treated effluent.
- g. Water with suspended solids concentrations higher than 20 g/ℓ cannot be clarified easily because the flocculant cannot be distributed throughout the slurry before it becomes absorbed and therefore some solids remain untreated. Therefore, Dow concluded that, for the flocculants tested, dredged material supernatants with relatively low concentrations of suspended solids, such as those encountered at weir outflows, can be effectively clarified.

9. An extensive investigation of the flocculation and sedimentation characteristics of high solids content (10 to 20 percent) dredged material slurries was recently reported by Krizek, Roderick, and Jin (1974). Five different materials dredged from four locations in the Great Lakes were treated with various chemical flocculants that were

selected on the basis of an extensive literature review. The results obtained from column settling tests and hydrometer tests are as follows:

- a. Calcium oxide and calcium chloride were effective flocculants for most of the dredged materials, and the supernatant suspensions were colorless and clear. In particular, the addition of 4 percent (based on the dry weight of the solids) calcium oxide flocculated all samples effectively. Chemical costs for treating a dredged material slurry with a solids content of 10 percent would be about $80/1000 m^3.
- b. Selected o-nitrophenol, p-nitrophenol, and tri-nitrophenol compounds were effective flocculants, but the associated supernatants although free of turbidity, exhibited a yellow and pink color. The undesirable coloration and the possible toxicity of the chemicals suggest that these additives are not acceptable as flocculants for use in disposal areas.
- c. Acetic, phosphoric, sulfuric, nitric, and hydrochloric acid, and aluminum sulfate were somewhat effective flocculants, but the supernatant suspensions were cloudy and had a brownish-yellow coloration after a day of settling.
- c. Calcium carbonate was quite effective as a flocculant for three of the dredged materials, and sodium chloride was effective for two; however, the supernatant suspensions remained cloudy after treatment with both chemicals.
- e. The organic chemicals (p-benzoquinone, pyrogallol, polyvinyl alcohol, and Krilium) were not effective flocculants. Resorcinol was somewhat effective with only one dredged material, but the supernatant suspension remained cloudy.

10. Based on the information presented or referenced above, the following conclusions can be advanced for the use of flocculants in fresh water environments:

- a. Flocculation can be effectively used to clarify supernatants and effluents from dredged material confinement facilities.
- b. The effectiveness of various chemical flocculants varies according to the characteristics of the dredged material and the concentration of suspended solids.
- c. For slurries with a high concentration (10 to 20 percent by weight) of suspended solids, calcium oxide (lime) appears to be a very effective flocculant. Most of the organic compounds tested do not appear to be effective flocculants.
- d. For slurries with low concentrations (up to 20 g/ℓ) suspended solids, organic polyelectrolytes are very effective flocculants.

Sedimentation

11. In a typical diked containment area, the dredged material slurry is pumped into the disposal site at one point and the supernatant waters are discharged at a point approximately opposite the inflow point. The concentration and nature of the suspended solids in the effluent supernatants depends on the concentration and nature of the inflow slurry, the size of the disposal area, the relative location of the discharge pipe and the effluent sluicing device, the degree of channelization in the flow, the retention time of the fluid, the direction and velocity of the wind, and the extent of the vegetation. Since the sedimentation regime that exists in a disposal area affords one of the primary means by which suspended solids can be controlled in the effluent (whether they exit over a weir or through a filter), it is appropriate in this study to consider in some detail the beneficial effects and economics of the sedimentation process. A review of the literature has revealed no model or methodology, theoretical or empirical, that is capable of predicting with any degree of confidence the sedimentation regime in a disposal area.

12. Krizek and Salem (1974) reported data on the spatial distribution of sediments in the Riverside and Penn 7 disposal areas near Toledo, Ohio, and those data are summarized in Figure D1. Thirty-seven tube samples (Hummel and Krizek, 1974) were obtained from Riverside Site from seven boreholes along Line 1, which connects the overflow weir with the inflow pipe, and auger samples were obtained from three boreholes along each of Lines II, III, and IV, which emanate radially at 45° spacings for a short distance from the end of the inflow pipe. Thirteen tube samples were taken from the Penn 7 site at the four designated locations. All samples were tested in accordance with standard procedures wherein a dispersing agent was used in the hydrometer test. These data were then combined to develop an appreciation for the actual distribution of particle sizes between the inflow pipe and the overflow weir and in the vicinity of the inflow pipe.

13. The longitudinal variation of grain-size characteristics was

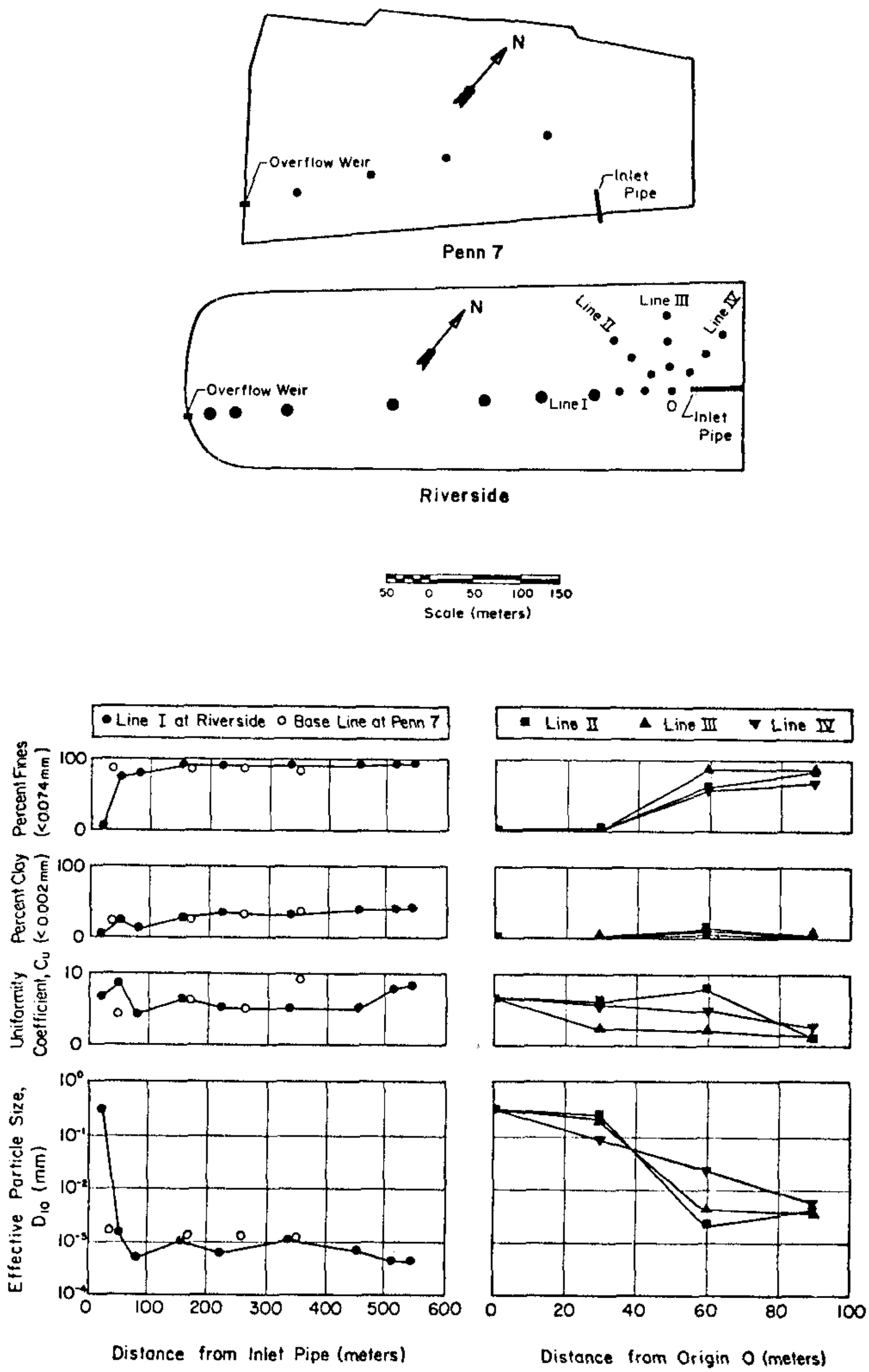

Figure D1. Spatial Variation of Sediment Gradations in Disposal Areas evaluated by plotting average values of the effective size, D_{10}, uniformity coefficient, C_u, percent clay (< 2μ), and percent fines (< 0.074 mm) for each location versus the horizontal distance of each respective location from the inflow pipe, and the results are given in Figure D1. The effective size, D_{10}, is seen to decrease from about 0.3 to 0.0015 mm in a distance of 30 m (100 ft). In the following 300 m (1000 ft), the effective size fluctuates between 0.0005 and 0.001 mm with no definite trend; this can be explained by the fact that particles may travel horizontally at different velocities while sedimentation is taking place. A gradual decrease in D_{10} from about 0.001 to about 0.0005 mm is noted in the vicinity of the overflow weir where the water normally covers the site. The coefficient of uniformity, C_u, has an average value of about 5 in the middle 400 m (1300 ft) of the site and about 7 near the inflow pipe and the overflow weir. The clay sizes are generally missing near the inflow pipe, but they gradually increase with distance to a maximum of about 40 percent. The abnormally high percent clay (25 percent) at Borehole 1 may be due to a pool of stagnant water at this location. The fines (<0.074 mm) increase from virtually zero to about 90 percent in 160 m (500 ft) and remain practically constant thereafter for a distance of about 300 m (1000 ft), after which they increase slightly to about 95 percent near the overflow weir. Analogous data from the Penn 7 site manifested generally similar trends; the observed differences are probably due in large part to the different flow patterns that prevailed at the two sites.

14. Six samples from Line II, thirteen from Line III, ten from Line IV, and one surface sample from the origin, 0, were analyzed to identify any radial variations in the grain-size distributions, and the average values of pertinent parameters at each borehole are plotted in Figure D1 versus the distance from the origin. The effective size, D_{10}, decreased from 0.3 to about 0.005 mm in about 90 m (300 ft), and the coefficient of uniformity, C_u, tended to decrease from about 7 at the origin to about 2 at 90 m (300 ft). The clay fraction increased from zero in the first 30 m (100 ft) to about 5 to 10 percent in the following 60 m (200 ft), but the fines (< 0.074 mm), which were almost

zero in the first 30 m (100 ft), increased dramatically to an average of about 70 percent at 60 m (200 ft) and then slightly more to an average of about 80 percent at 90 m (300 ft).

15. Based on the foregoing data, the following observations can be made for the sedimentation regimes that prevailed in the indicated two disposal areas:

a. Practically all of the coarse-grained materials (equivilent diameter larger than 74μ settled out of suspension within a distance of 90 m (300 ft) from the inflow pipe.

b. For the remainder of the distance between the inflow pipe and the overflow weir in each area, the spatial distribution of grain sizes was essentially independent of distance, except in the immediate vicinity of the overflow weirs where the portion of submicron sizes increased somewhat.

c. The lack of any definitive depositional pattern can be explained partly by the fact that the discharge of effluent during active dredging seasons was interrupted periodically by long periods of water retention, during which time the suspended particles had ample opportunity to settle out of suspension over the entire site.

d. Since the effective grain size of the material that settled out of suspension over most of the disposal area is about 1μ with uniformity coefficient of about 5, the majority of the particles that passed over the weir was probably of submicron diameter.

e. Taking into consideration the fact that most of the dredgings from the Toledo area contain only a small fraction of submicron size particles, it can be concluded that these disposal areas provided sufficient sedimentation time to allow most of the suspended solids in the supernatants to settle out. This conclusion is varified by data reported by Krizek,Gallagher, and Karadi (1974) on the quality of the effluents from one of these disposal areas (the average concentration of total solids in the effluent of Penn 7 over a typical four-month period was 0.043 percent on a weight basis).

16. Theories to describe sedimentation in an ideal regime of horizontal laminar flow were developed over 70 years ago (Hazen, 1904) and subsequently modified and extended (Camp, 1946). Methodologies were then advanced to account for the effect of nonideal mixing and dispersion in real basins, and significant effort has been made in

recent years to develop models to predict sedimentation patterns for cases of discrete or flocculated particle settling. Felderman and Eno (1975) developed a mathematical model to predict sedimentation patterns in shallow (10 ft deep) small (several acres) lakes that are characterized as settling basins that receive influents but have no outflow; wind stress and flow currents were taken into account. Preliminary verification of the model has been obtained.

17. Yao (1975) analyzed the phenomenon of extended plain sedimentation without coagulation. He concluded that for long detention times (on the order of days) this method can reduce significantly the quantities of particles affected by Brownian motion; although micron sized particles will not settle for short detention times, extended sedimentation will allow them to settle and thus reduce significantly the turbidities of surface waters.

18. A general simulation model of discrete settling in a real basin has been developed by Chang (1972), and Lin (1975) has extended Chang's treatment to include flocculent settling. The model quantitatively accounts for fluid dispersion, turbulent mixing, and hindered settling; and it assumes that differential settling of the given influent grain-size distribution accounts for flocculent settling. Basin efficiency is given as a function of grain-size or total mass. Good agreement of model results with available experimental observations and with Hazen's real tank sedimentation theory has been found. For flocculent settling the model predicts that settling times can be reduced by at least a factor of two. However, further comparison between theory and experiment is desirable before results from such models are used directly for design.

19. An attempt was made to use Hazen's sedimentation theory to estimate the proportion of soil particles of different sizes that will be retained by discrete sedimentation in a disposal area. In the absence of any documented, more sophisticated analysis, this method may be used to obtain a first-order approximation of the sedimentation regime in a dredged material containment facility.

Settling velocity of
discrete particles

20. A discrete particle is one that does not alter its size, shape, and weight during settling. When such a particle settles through a quiescent fluid, it will accelerate until the frictional resistance or drag of the fluid equals the impelling force of gravity acting upon the particle; subsequently the particle will settle at a uniform velocity. By equating the drag and buoyancy forces an expression for the uniform settling velocity, v_s, can be found. At low Reynolds number ($R \lesssim 1$), the drag is due solely to viscous forces, and the expression for v_s can be written as

$$v_s = \frac{\gamma_s - \gamma_f}{18\mu} D^2 \text{ (Stoke's Law)} \qquad \text{(D1)}$$

where γ_s is the unit weight of the solid particle, γ_f is the unit weight of the fluid, μ in the absolute viscocity of the fluid, and D is the equivalent diameter of the settling particle.

Efficiency of an
ideal settling basin

21. In order to devise a framework for the formulation of sedimentation in continuous-flow basins, certain simplifying assumptions must be introduced (Fair and Geyer, 1966); these are:

a. Within the settling zone of the basin, sedimentation takes place exactly as in a quiescent container of equal depth.

b. The flow is steady and, upon entering the settling zone, the concentration of suspended particles of each size is uniform throughout the cross section normal to flow.

c. A particle that settles out is not resuspended.

The proportion, P, of particles that are removed in a horizontal-flow basin is given (Hazen, 1904; Fair and Geyer, 1966) by the expression

$$P = \frac{v_s}{Q/A} \qquad \text{(D2)}$$

where Q is the mass rate of flow and A is the surface area of the basin. Therefore, for discrete particles and unhindered settling, the efficiency of a basin is solely a function of the settling velocity of the particles and the surface area and rate of flow through the basin, and it is independent of the depth of the basin and the detention period.

Reduction of basin
<u>efficiency by currents</u>

22. The efficiency of settling basins is reduced by (a) eddy currents caused by the inertia of the incoming fluid, (b) wind-induced currents when basins are not covered (more predominant in deeper basins), (c) thermal convection currents, and (d) density currents (cold heavy water flows beneath the warm lighter water on a basin surface). Each of these currents may contribute to short-circuiting the flow or upsetting the quiescent settling process. According to Hazen's theory, the proportion, P, of particles removed in a real basin where currents reduce the efficiency is

$$P = 1 - \left[1 + \frac{1}{n}\frac{v_s}{Q/A}\right]^{-n} \qquad \text{(D3)}$$

where n is a performance coefficient for the basin and ranges from unity (very poor performance) to infinity (ideal plug flow).

Application to dredged
<u>material disposal areas</u>

23. A dredged material containment facility can be visualized as consisting of two zones. In the first zone, which consists of the vicinity around the discharge pipe, the fill surface varies significantly and randomly; channelization of flow occurs; slurry concentration is very high; and sediments are frequently disturbed and resuspended because of disposal operations. In the second zone, which can be considered to act as a sedimentation basin, a slow, essentially horizontal flow prevails in a completely and continuously inundated area with a relatively constant width.

24. The application of Equation D1 for particle sizes of 100μ or less is valid, because Reynolds numbers are less than unity; hence, Stoke's Law is reasonably applicable in the sedimentation regime of a

disposal area. For a specific gravity of solids equal to 2.67 and a water temperature of 20°C, Equation D1 can be simplified to

$$v_s = 9{,}000\ D^2 \qquad \text{(D4)}$$

where v_s is in cm/sec when D is expressed in cm.

25. Since the efficiency of settling in a real disposal area will be reduced by currents, the use of Equation D3 with a performance coefficient of unity (to be conservative) in conjunction with Equation D4 yields an expression for the removed portion, P, of the particles with diameter D:

$$P = 1 - \left[1 + \frac{9000\ D^2}{Q/A}\right]^{-1} \qquad \text{(D5)}$$

where Q/A and D are expressed in cm/sec and cm, respectively.

26. The removal efficiency of a disposal area for suspended particles of different sizes can be computed from Equation D5 when the discharge and the surface area are known. As an example, consider a disposal area for which (a) the discharge is 0.1 m^3/sec (310,000 cu ft per day); (b) the width is 100 m (300 ft); and (c) the length of area continuously under water is 300 m (1000 ft). For a depth of water equal to 2 m the theoretical detention time of such a basin is about 7 days. For suspended particle sizes equal to 10, 3 and 1μ, the removal efficiency is 96, 71, and 21 percent, respectively. Further, assume that the discharge remains the same, but the size of the disposal area is decreased to a width of 50 m (165 ft) and a length 100 m (330 ft); for this case, the removal efficiencies for the same particle sizes are 82, 29, and 4 percent, respectively.

27. Based on the foregoing information, the following conclusions can be advanced:

- a. Sedimentation, with or without chemical pretreatment, is a solids-liquid separation technique that is and should be widely used for clarification of disposal area supernatants.

b. Given adequately large disposal areas, sedimentation alone may be sufficient to obtain effluents of the desired quality; however, other factors, such as land cost, secondary use, and site recovery, may preclude the use of this alternative.

c. Since sedimentation patterns in disposal areas have not been investigated in any detail, it is necessary to adapt theories of sedimentation basin operation to obtain a first-order approximation of disposal area retention efficiency by sedimentation alone; however, the limited amount of data available lend reasonable support to this approach.

Mechanized Surface Filtration

28. Surface filtration systems depend primarily on physical straining processes that can be described as those processes that remove solids by virtue of physical restrictions on a medium that has no appreciable thickness in the direction of liquid flow. These systems can be separated into those that are used for dewatering thick slurries (vacuum filters, centrifuges, filter presses, and belt filter presses) and those that clarify waters with very low concentrations of suspended solids (wedge wire screens, microscreens, and precoat filters). Each of these systems is discussed separately in the following sections.

Rotary vacuum filters

29. In the United States, vacuum filtration is the most commonly used mechanical sludge dewatering method. Process efficiency is largely governed by the media opening and the size distribution of solid particles. Filter-cake formation is accomplished first by a bridging of the medium with larger particles followed by a packing of the pores near the filter medium with fine particles. Chemical conditioning eliminates large numbers of small particles and is generally considered necessary for the efficient use of vacuum filtration equipment. A large number of additional factors also affect the performance of vacuum filters and must be considered in the design of an efficient unit: the amount of solids in the feed slurry and the allowed form time influence the yield of the unit; the drying time affects the moisture content of the cake produced; chemical conditioners and vacuum level affect the

specific resistance; and the type of fabric, the particle sizes, and the organic content affect the cracking tendency of the cake, the required vacuum, and the air throughput. The most common devices are rotating drum filters, continuous belt filters, and rotating disk filters. Rotating drums have been designed with surface areas up to 50 m^2 (500 ft^2), and rotating disk filters with surface areas up to 250 m^2 (2500 ft^2).

30. The feed solids to vacuum filters typically range between 1.4 and 7 percent for different types of sludges or slurries (Weber, 1972), but they can be as high as 40 percent for clay slurries (Dickey, 1961). For clay slurries the cake moisture usually varies from 15 to 80 percent (a 60 to 80 percent vacuum is used) and the hourly yield in dry weight of solids ranges from 10 to 50 kg/m^2 (2 to 10 lb/ft^2). Since clay slurries resemble many types of dredged material, these ranges might be considered typical for vacuum filtration of dredged material. With the assumption that a 10 percent solids influent is fed to a rotary drum vacuum filter system at a flow rate of 0.15 m^3/sec (3.7 mgd), the required surface area of the filter would be about 1000 m^2 and a battery of 20 rotary drum filters with a surface area of 50 m^2 each would be needed. The use of vacuum disk filters with surface areas of 250 m^2 each would require only 4 units (perhaps few enought to consider the incorporation of such a system on a barge, which may be employed as a transfer station for dredged material). Removal efficiencies for vacuum filters can be as high as 99 percent, depending on media size, pretreatment, and chemical conditioning.

31. Capital costs for rotary vacuum filters range from 1,000 to 3,000 dollars per square meter of filter area (Eckenfelder, 1970; EPA, 1974), depending on the size of the unit, type of media, and auxiliary equipment. The operation and maintenance costs vary widely, but 5 to 30 dollars per ton of dry solids produced is considered representative (Burd, 1968; EPA, 1974); however, a pilot test is usually required to obtain a meaningful cost assessment for a particular application.

Centrifugal dewatering

32. The use of centrifugal forces as the driving force in

filtration or to accelerate the sedimentation of particles from the fluid constitutes an important development in solid-liquid separation. Technological developments in centrifugation have led to a very large variety of machine types, each designed for a particular process but often finding use in many other fields.

33. Although centrifuges can remove suspended particles that are smaller than 1μ in diameter, their removal efficiency is reduced dramatically for particles smaller than 10μ (Tiller, 1972). For this reason, chemical conditioners are usually added to the feed slurry to increase particle size. In wastewater sludge treatment (EPA, 1974), solids in the feed water can be as high as 35 percent and recoveries up to 95 percent are realized. However, chemical conditioners (polymers) must be used typically in amounts of 1 to 3 kilograms per ton of dry solids recovered and at a cost of about 2 to 5 dollars per ton of solids recovered. Burd (1968) reported that operating and capital costs for centrifugal dewatering of sludges range from 14 to 28 dollars per ton of recovered solids.

<u>Filter presses</u>

34. The plate and frame filter press consists of vertical plates that are held rigidly in a frame and are pressed together between a fixed and a moveable end. On the face of each plate is mounted a filter cloth. Slurry is continuously fed into the press until all chambers between the plates are filled, and dewatering continues until there is no filtrate produced. The press is opened; the dewatered slurry is removed; the plates are cleaned; and the cycle is repeated. For the treatment of wastewater sludges it is reported (EPA, 1974) that filter presses can accomodate loads of influent suspended solids from 4 to 10 percent, and produce cakes with 45 to 50 percent solids, and have excellent effluent quality (10 to 75 mg/ℓ for reported cases).

35. The advantages of pressure filtration over vacuum filtration are (a) higher cake solids concentration (30 to 50 percent), (b) improved filtrate clarity, (c) improved solids capture, and (4) reduced chemical consumption. The disadvantages are (a) batch operation, (b) high labor costs, (c) filter cloth life limitations, and (d) the frequent

necessity of cake delumping.

36. The addition of chemicals to the influent slurry is still a requirement to achieve effective performance from a filter press. Precoat by diatomaceous earth, fly ash, and other filter aids has been used advantageously in certain filter press applications.

37. The Cedar Rapids plant was used as an example to obtain a cost estimate. The system includes two filter presses, each having about 300 m^2 (3,400 ft^2) filter area, and handles digested sludge with about 5 percent solids. Reported costs per ton of dry solids recovered are 4.7 dollars for operation, 9.7 dollars for capital investment, and 7.3 dollars for chemicals.

38. The Dyno Filter (marketed by Artisan Industries, Inc.) was recently introduced to the market and is an improvement over conventional filter presses because it allows for continuous operation. When tested with kaolinite and feldspar slurries containing 28 to 56 percent solids in the feed water, the unit produced a cake with 57 to 77 percent solids (30 to 75 percent water content). Of particular concern to the dredged material disposal problem is the fact that typical units presently available have small capacity.

Belt systems

39. A variety of mechanized surface filtration systems are designed so that the filter medium forms a continuous belt. Vacuum and/or pressure or squeezing action is used to dewater the feed slurries. The squeegee dewatering unit (Westinghouse - Infilco, 1971) uses capillary dewatering action followed by pressure dewatering via rollers to handle slurries with 0.5 to 1 percent solids and produce cake with up to 18 percent solids content. Compared to vacuum filtration, this system can reduce total capital, maintenance, and operation costs by more than 50 percent.

40. The Tower Belt Filter (Alt, 1974), a recent invention, uses a pressure belt system that permits some cake filtration prior to compression. The slurry is fed into the top of the system between two endless belts that are fixed to taper the sludge zone until the sludge reaches compression rollers, which squeeze the already partially

dewatered cake. Blinding is reduced by allowing some drainage (under pressure) prior to compression and permitting the coarser particles to settle onto the filter cloth at lower parts of the belt.

Wedge wire screens

41. Inclined or rotating wedge wire screens are a relatively new development for raw wastewater treatment. The Hydrasieve (made by C-E Bauer, Division of Combustion Engineering, Inc.) and the Hydroscreen (made by Hydrocyclonics Corporation) are typical examples of devices that use wedge wire screens. The screen wires are triangular in cross section and are spaced 0.25 to 1.5 mm apart. The influent waters flow over the screen; the fluid passing through the screen is the effluent of the system, and the extracted solids move downward on the screen, where they are collected and removed. At the present time about one dozen municipal treatment plants use wedge wire screens as part of their pretreatment and primary treatment processes (EPA, 1975b).

42. Although inclined screens cannot remove suspended solids to the same extent as a sedimentation tank, they have been received favorably by the profession because they do an excellent job of removing trashy materials, which may foul subsequent sludge handling units. Their ability to remove fine grit is limited by size openings, and separate equipment should be used after the screen for this purpose. The suspended solids removal obtained by wedge wire screens varies between 5 and 25 percent (EPA, 1975b). Available units can accomodate flow quantities from 750 to 55,000 cubic meters per day (0.2 to 14.5 mgd), depending on their size. Little quantitative work has been done on the solids loading capacity of a hydrasieve, but, in general, good performance requires that the influent be sufficiently dilute to allow smooth flow over the weir.

Microscreens

43. A microscreen unit usually consists of a motor-driven rotating drum mounted horizontally in a rectangular chamber, with a fine screening medium covering the periphery of the drum. Influent waters enter the drum interior through the open end and pass radially through the screen, depositing solids on the inner surface of the

screen. At the top of the drum, pressure jets of effluent water are directed onto the screen to remove the mat of deposited solids. Microscreen fabrics normally are woven of stainless steel or synthetic fibers with openings in the range of 15 to 60μ. Microscreeners have been used principally for removing algae and other microorganisms, and removal efficiencies from 50 to 90 percent have been obtained, depending primarily on the species involved. Available data on the performance of microscreen units in secondary effluent treatment indicate removal efficiencies from 45 to 85 percent with influent concentrations of suspended solids from 10 to 65 mg/ℓ. Microscreeners can be designed to accomodate flows up to 15,000 cubic meters per day.

44. The functional design of a microscreen unit involves (a) the characterization of the suspended solids with respect to concentration and degree of flocculation (these factors have been shown to affect microscreen capacity, performance, and backwashing requirements) (b) the selection of unit design parameters, and (c) the provision for backwash and supplemental cleaning facilities. The design parameters for microscreen units, together with their typical values, are (a) screen mesh (20 to 25μ), (b) submergence (75 percent of height; 66 percent of area), (c) hydraulic loading (5 to 10 gpm/ft^2), (d) head loss through screen (7.5 to 15 cm), (e) peripheral drum speed (7.5 cm/sec at 7.5 cm head loss; 60 to 75 cm/sec at 15 cm head loss), (f) typical drum diameter (10 ft), and (g) backwash flow and pressure (2 percent of throughput at 5 psi; 5 percent of throughput at 15 psi). Capital costs are in the neighborhood of 4,000 to 5,300 dollars per 1,000 cubic meters per day (15,000 to 20,000 dollars per mgd). Operation and maintenance costs are about 0.25 to 0.50 dollars per 1000 cubic meters (1 to 2 dollars per million gallons) treated (EPA, 1975b). Eckenfelder (1970), however, reported costs that are about double the EPA values.

45. Although microscreens have been in use for more than thirty years for secondary effluent treatment, suitable relationships have not been developed to allow quantitative predictions of their performance and pilot studies are still required. However, some general

conclusions can be advanced about the use of microscreen as a device for removing suspended solids from secondary effluent (EPA, 1975b):

- a. Under the most favorable operating conditions, microscreen units can reduce suspended solids to concentrations as low as 5 mg/ℓ.
- b. Although the suspended solids removal pattern is irregular, the performance tends to be better for lower hydraulic loadings.
- c. Increases in influent suspended solids are reflected in the effluent, but with noticeable damping of peaks.
- d. Microscreens are useful in place of clarifiers to polish the effluent from low rate trickling filters, provided the solids are generally low in concentration and are well flocculated.

46. The FMC Corporation has developed a sophisticated, but nonetheless relatively simple, device for filtering waters by use of a microscreen. This unit uses a highly efficient combination of hydraulic and ultrasonic energy to keep the filter fabric clean of solid particles, thereby allowing high hydraulic loadings and high quality filtrates (Monroe and Pelmulder, 1973). The strainer has been extensively tested with many types of wastewaters, and it was found to have removal efficiencies generally greater than 90 percent and frequently up to 99 percent. It is not known whether this efficiency is also obtained for particles with dimensions of a few microns, as claimed by the manufacturer. The hydraulic capacity of the strainer varies with the concentration of suspended solids; it was found to range from 0.5 gpm/ft^2 at high concentrations of suspended solids (over 20 g/ℓ) to 30 gpm/ft^2 at low concentrations of suspended solids (10-150 mg/ℓ). Available units can handle up to 3 mgd at low concentrations of influent suspended solids.

<u>Precoat filtration</u>

47. This filtration process uses a thin layer of precoat formed around a porous septum to strain the suspended solids from the influent that passes through the filter cake and septum. The filter medium used is a thin layer of diatomaceous earth or perlite, and this material is wasted at the end of each filter cycle. The cycle of filtration

consists of three steps; namely, (a) precoat application, (b) filtration, usually accompanied by the application of body feed, and (c) filter cake removal. About 0.05 to 0.10 grams of diatomite or perlite per square centimeter are used to form the precoat. Due to hydraulic compression of the solids retained on the precoat, the filter cycles may be very short unless additional filter aid (body feed) is added during the filtration period. The use of body feed results in a filter cake that is more porous and less compressible, thereby extending the period of the filter run. For applications in secondary effluent treatment, the amount of body feed required varies from 10 to 50 mg/ℓ of influent.

48. Precoat filters can be pressure filters, in which the raw water is pumped into and through a filter contained in a pressure vessel, or vacuum filters, in which a suction is created on the filtered water side of the septum. Precoat filters have been used for many years in industrial filtration applications. Their application to water filtration developed largely during World War II for cyst and cercaria removal, and their use in municipal water treatment is increasing. Recent studies have indicated that (a) body feeds of about 6 mg/ℓ per JTU of turbidity should be used and (b) influent suspended solids should be very low (3 to 13 mg/ℓ or turbidity less than 10 JTU). Capital costs, exclusive of buildings, are about 20,000 to 30,000 dollars per mgd for manually operated plants and 30,000 to 60,000 dollars per mgd for automated plants. Operating costs are a strong function of raw water quality because filter aid requirements increase as water quality decreases. Diatomite costs about 5 cents per pound delivered. Based on available information (Weber, 1972; EPA, 1975b), the following general conclusions can be drawn on the current use of precoat filters:

a. Precoat filters manifest good turbidity removal; all particles larger than 1μ can be removed, but the efficiency is low for colloidal-size particles without pretreatment.

b. The required amount of body feed and the associated cost limit the range of turbidities that can be treated to not more than 10 or 20 JTU.

c. Precoat filtration, as presently practiced, is suitable only for secondary or tertiary suspended solids removal and to polish effluents from other filtration units.

Mechanized Granular Media Filtration

49. Granular media filtration involves the passage of water through a deep bed of granular material with a resulting deposition of solids. Eventually, the head loss across the bed becomes excessive or the ability of the bed to remove suspended solids is impaired, and cleaning is then necessary to restore the operating head or the flow and effluent quality to acceptable levels. Most filters operate on a batch basis, wherein the entire unit is removed from service for periodic cleaning. Traditionally, this filtration process is employed in water treatment, with or without pretreatment by coagulation and sedimentation, to remove suspended solids and in wastewater treatment to remove biological flocs from the settled secondary treatment plant effluent.

Conventional designs

50. There are three basic methods of operating filters, and these differ primarily in the way that the pressure drop (driving force) is applied across the filter: (a) constant-pressure filtration, (b) constant-rate filtration, and (c) variable declining-rate filtration (Cleasby, 1969).

51. In true constant-pressure filtration, the total available pressure drop is applied across the filter throughout the filter run. As the filter clogs with solids, filter permeability decreases and, since the pressure drop remains constant, the flow rate decreases. This method of filtration requires a relatively large volume of water storage.

52. In constant-rate filtration, a constant pressure drop is maintained across the filter, but the flow rate is also held constant by means of a flow control valve. This system has the disadvantages of higher initial and maintenance costs for the rate-control system and filtrate quality is not as good as that obtained from the declining-rate filter operation. To overcome these disadvantages, systems have been designed to incorporate a flow splitting influent weir, thereby eliminating rate controllers.

53. Variable declining-rate filtration is an alternative to both constant-pressure and constant-rate operations. Such units have the advantages that no rate controllers are used and dirty filters are taken out of operation by a gradual increase in flow rate for the clearer filters. This results in better effluent quality for longer filter runs with less head required.

54. The granular filters commonly used are either operated under several feet of fluid head by gravity flow (gravity filters) or enclosed completely in a pressure tank (pressure filters). Gravity filters can be designed to meet any capacity, but it has been common practice to construct them in some even multiple of 0.5 mgd capacity up to 5 mgd (2,000 to 20,000 cubic meters per day) so that standard appurtenances can be used. When the containment structure is to be fabricated on site, the filter box is usually designed as shallow as practical to reduce the construction cost for the concrete walls. Total depth includes the sum of the underdrain depth, filter medium depth, maximum operating depth of water above the filter medium, and freeboard. Common operating water depths are 3 to 5 ft (1 to 1.5 meters). Pressure filters are placed in closed, watertight tanks which may stand either horizontally or vertically. Their action is identical to gravity filters; the same filter media are used; and similar flow rates are realized. However, filter runs of longer length are possible, because many more solids may be retained before backwashing is required.

55. Media commonly used in mechanized granular media filtration include silica sand, althracite coal, and perhaps garnet or ilmenite in special multi-media designs. Common specifications require sands with an effective grain size of 0.45 to 0.55 mm and a uniformity coefficient not greater than 1.65 in depths of 0.60 to 0.75 m. For dual media designs a layer of anthracite is frequently used over a layer of sand; typical anthracite/sand filters may include from 0.30 to 0.60 m of anthracite and from 0.15 to 0.40 m of sand. Common specifications for anthracite dictate an effective grain size from 0.6 to 1 mm and a uniformity coefficient less than 1.8 (Weber, 1972; Tiller, 1972; EPA, 1975b).

56. Granular filters are washed to restore their capacity when the effluent quality becomes unacceptable or when the pressure drop (head loss) through the filter reaches a predetermined value. Filter runs in different plants vary from 12 hours to several days, one day being considered an acceptable average value. The filter is usually washed by reversing the flow of water through the filter at a rate adequate to lift the grains into suspension, causing fluidization and expansion of the filter bed. The chief mode of particle cleaning is hydrodynamic shear with particle-to-particle contact of lesser importance. The wash waters are collected and either recycled through the plant or treated separately. To maintain a continuous flow, each filter unit consists of more than one cell, usually four or more; this allows backwashing of one or two cells while the others continue their filtration activity.

57. Filter sizes are determined according to the expected amount of water to be treated in a unit. However, in order to facilitate the distribution of raw water and the collection of backwash water effectively, the maximum size of any filter cell should be limited to about 80 m^2 (Tiller, 1972). Underdrainage systems support the filter medium, distribute the backwash waters evenly, collect the filtered water, and prevent the loss of filter medium with filtered water. To prevent the loss of filter medium a layer of graded gravel is often placed over the underdrainage system.

58. The usual concentration of suspended solids applied to granular media filters does not exceed a few hundred milligrams per liter and is generally lower than 100 mg/ℓ. Most data on the performance of systems for the filtration of effluents from wastewater treatment plants (Tiller, 1972; EPA, 1975b) show ranges of (a) influent suspended solids loads from 2 to 150 mg/ℓ, (b) removal efficiencies from 10 to 99 percent, (c) run lengths from 1.5 to 150 hours, and (d) throughput rates from 0.05 to 2 cm/sec (0.6 to 30 gpm/ft^2). In general, the efficiency of granular filters is found to be excellent (Weber, 1972; Tiller, 1972; EPA, 1975b) for particles or flocs of large sizes (above 50μ), but particles of 3 to 5μ are much less efficiently removed.

Therefore, typical sand filtration procedures are inextricably bound to the coagulation or flocculation process, and the two should be considered together.

59. Costs involved in granular media filtration are even more difficult to obtain than operating experience data (Tiller, 1972). According to Eckenfelder (1970), capital costs range from 5,000 to 25,000 dollars per 1000 m^3 treated daily, and operation and maintenance costs range from 5 to 20 dollars per 1000 m^3. Lynam and Bacon (1970) reported operation and maintenance costs of 6 dollars per 1000 m^3 for a plant with a daily performance capacity of 40,000 m^3.

60. The following general observation can be made for mechanized granular media filters as they are used today in solid-liquid separation technology:

- a. The influent loads of suspended solids seldom exceed 100 to 200 mg/ℓ.
- b. For such loadings, removal efficiencies up to 99 percent can be realized.
- c. Any amount of flow can be accomodated by providing adequate filter surface area in single- or multiple-cell filters.
- d. Suspended solids of submicron sizes cannot be removed efficiently, and pretreatment to increase particle size is required.
- e. The costs associated with using filter depths greater than 0.75 to 1.0 m are not commensurate with a proportional increase in effectiveness.
- f. All mechanized granular filters require backwashing and facilities to dispose of the wash water and retained solids.

Special designs

61. A number of special designs for mechanized granular media filters have been developed in recent years to overcome (a) the need to stop the filtration process periodically to clean the filter medium, (b) the limited ability to handle waters with high concentrations of suspended solids economically, and (c) excessive operation and maintenance requirements and costs. These designs include gravity and pressure filtration units, upflow systems, and moving bed filters.

62. Gravity filters. The Sybron Corporation (1972) has developed an automatic gravity filter (Permutit, AVGF) system that eliminates the use of valves and feed and backwash pumps, as well as the need for manpower and maintenance. Depending on their size, these units can accomodate flows from 8 to 300 m^3 per hour and can operate for up to 2 days before washing is necessary. The Ecodyne Corporation (1971) markets a series of automated gravity filters. The Mono-scour filter is a heavy-duty, high-rise filtration unit that can operate efficiently for high concentrations of influent solids. Backwash cycles are automatically initiated and only one valve is used to control the inflow rate, thus reducing manpower and maintenance requirements substantially. Hardinge Corporation (EPA, 1975b) has developed a fine media (0.48 mm sand), multi-compartment filter in which each compartment can be backwashed without stopping filtration in the remainder of the filter. In order to achieve longer runs, many manufacturers have introduced fully automatic, shallow bed sand filters that have a provision for diffusing air in the water above the filter bed to resuspend the solids collected on the media surface; one typical example of such a system is marketed by the Hydro-Clear Corporation (EPA, 1975b).

63. Pressure filters. The Dravo Corporation (1970) has developed a deep-bed pressure filter that can effectively clarify waters with concentrations of suspended solids up to 1 g/ℓ and can produce effluents with concentrations of suspended solids as low as 1 mg/ℓ. This system can have throughput rates from 0.1 to 1 cm/sec and the backwash cycles are automatically controlled. The Hayward Filter Company provides an easily automated system that has high throughput rates (up to 1 cm/sec) and can effectively clarify up to 20 m^3 per minute of waters with suspended solids loads up to 2 g/ℓ.

64. Upflow filters. In downflow single-media filtration, the bed, after backwashing, is graded from fine to coarse in the direction of flow. This disadvantage can be eliminated by using upflow filtration, which has better efficiency than downflow for similar filter media, bed sizes, and flow rates. Smith, Scott, and MacInnes (1973) showed that upflow filters loaded with 700 mg/ℓ of suspended solids (without

pretreatment) produced effluents with 1 mg/ℓ of suspended solids and sustained runs up to 2 days at flow rates of about 0.3 cm/sec, and they concluded that upflow filters had 8 to 10 times the sediment-holding capacity of downflow filters. The FMC Corporation (1973) and the Zurn Industries, Inc. (1971) have developed upflow granular filters. The latter was evaluated in a pilot study by Filipkowski and Strudgeon (1973) and found to have an average removal efficiency of 93 percent at a flow rate of 0.75 cm/sec. The FMC system avoids the use of valves by incorporating a leaping weir design, thus reducing maintenance problems. Both systems operate most effectively at low concentrations of suspended solids (up to 200 mg/ℓ).

65. Moving-bed filters. The basic concept of a moving-bed filter is the mechanical movement of the most heavily clogged portion of the granular medium out of the zone of filtration with virtually no interruption of the filtration process. The major potential of such a process lies in its ability to operate at high flow rates and at much higher solids loadings than conventional systems; superior cleaning of the filter media is also possible. The Johns-Manville Corporation (Libby, Bell, and Wirsig, 1972) has developed a moving-bed filtration system, which was evaluated for the treatment of raw domestic and industrial wastewaters, primary effluent, and settled or unsettled trickling filter effluents. For various conditions loads of suspended solids ranged from 50 to 150 mg/ℓ, and suspended solids removal efficiencies ranged from 70 to 91 percent. The flow rate through any unit or combination of units depends on the quality of the influent and the discharge requirements, and flow rates up to 7 gpm/ft^2 of exposed filter area are possible. The filter media used was quartz sand with an effective grain size between 0.6 and 0.8 mm and a uniformity coefficient of 1.5. Recently, Dravo Corporation (EPA, 1975b) has introduced a radial-flow, moving-bed filter; the main feature of this unit is the radial-flow concept, which provides more filter area per unit volume than downflow or upflow systems. As the liquid flows radially from a central core, it decreases in velocity and provides an increased opportunity for solids removal. Such a radial flow unit was tested on

biologically treated wastewater with up to 80 mg/ℓ of suspended solids at a flow rate of 4 to 6 gpm/ft^2, and it gave removal efficiencies between 60 and 80 percent. The Hydromation Corporation (EPA, 1975b) has also developed a radial-flow, moving-bed filter that uses a synthetic resin media, but information on its performance was not available.

66. General observations. The following general observations can be advanced for special mechanized granular media filtration systems:

a. A large variety of specially designed mechanized granular media systems are available.

b. Information on the performance capabilities of such systems has not been generally documented, regardless of claims by manufacturers. The EPA Technology Transfer publications provide an exception, but these are limited in scope (mainly removal of wastewater solids).

c. Certain systems may be capable of effectively handling suspended solids loads much higher than conventional systems (up to 2 g/ℓ compared to about 0.1 g/ℓ).

d. Certain systems are completely automated and require a minimum of manpower and maintenance.

Nonmechanized Surface Filter Systems

67. This group of filter systems includes units where solids removal is accomplished by a physical straining action, and little or no mechanization is required for operation. Except for the case where sand is the filter medium (slow sand filters), reports on the use of nonmechanized systems are not generally available. However, as identified in Part 4, fibrous media (woven or nonwoven), nonconventional media (straw, wood chips, and sawdust), or gravel could function as surface filters.

Slow sand filters

68. A slow sand filter consists of a watertight basin containing a layer of sand 1.0 to 1.5 m thick supported by a layer of gravel 0.15 to 0.30 m thick. The gravel is underlaid by a system of open joint underdrains at 3 to 6 m center-to-center spacing, and these underdrains lead the filtrate to a single point of discharge. Commonly used sands

have effective grain sizes ranging from 0.25 to 0.35 mm and a uniformity coefficient of less than 3. The filter is operated with a water depth of 1.0 to 1.5 m above the sand surface. The majority of the solids are removed in the upper few centimeters of sand, and they form a biologically active slime layer (Schmützdecke). When the head loss reaches the physical limit of the plant (1.0 to 1.5 m), the filter is removed from service, drained, and cleaned; cleaning usually consists of removing the top 2 to 5 cm of sand. Flow rates are generally low (less than 0.1 cm/sec), and filter runs range from 1 to 6 months for the usual applications (secondary effluents). Removal efficiencies are good for suspended solids and bacteria (up to 99 percent), but they decrease considerably for fine clays and other colloidal solids (1μ or less in diameter); therefore, pretreatment may be necessary to increase the particle sizes (Weber, 1972). Although slow sand filters have not been used to clarify waters with high solids contents, runs for such cases are expected to be very short and the idle time may become significant.

Gravel filters

69. Properly designed layers of gravel have been used successfully for erosion control and as protective filters for retaining and preventing the migration of finer soils. However, for the particular objectives of this research effort, gravel filters appear to be of no use, other than to remove coarse debris and particles that could cause face clogging of finer media filters.

Nonconventional media

70. The use of straw, sawdust, wood chips, or wood shavings in filtration is a fairly novel and meritorious idea, since these media are readily available and relatively inexpensive. Depending on the density or degree of compaction, such media can function as surface and/or depth filters. However, information on their capabilities for removing suspended solids from waters is not available. The major disadvantage of such materials is the likelihood of producing highly colored effluents due to the leaching of humic substances, which may be considered as a pollutant to the receiving waters.

Fibrous media filters

71. The possibility of using fibrous media as components of nonmechanized filter systems appears to be very limited. Woven synthetic fiber cloths or wire screens can effectively retain suspended particles of various sizes, depending on their pore openings, but blinding of the filter surface occurs quickly and a mechanism is required to clean the medium continuously and remove the retained solids. For the removal of very fine suspended particles (1μ or less), woven fibrous media are usually very ineffective. Nonwoven fibrous media (like the Monsanto E2B and the Celanese Mirafi cloths) appear to have some potential in nonmechanized systems. These clothes can be used in multiple layers to increase their removal efficiency by depth filtration. However, pilot testing of any design would be required before recommendations are made.

Electrofiltration

72. The process of electrofiltration consists of electrophoresis and filtration. Electrophoresis is defined as the migration of electrically charged colloid particles in a direct current electrical field. Charged particles are forced to flow towards a membrane or other filter medium where they are then removed from suspension.

73. In recent years forced-flow electrophoresis has been gaining attention in the field of water and wastewater purification, and a wide range of possible applications has been suggested (Moulik, 1971). Although some rather sophisticated laboratory equipment has been developed to investigate this phenomenon, full-scale field installations are still far from materializing. Cooper, Mees, and Bier (1965) conducted a laboratory investigation of forced-flow electrophoresis to identify possible areas of field use, and they found that water with a concentration of suspended silt of 1500 mg/ℓ (flood runoff) could be effectively clarified by use of membranes with 5μ openings. The flow rates were about 2 gal/hr/ft^2 of filter area (0.0025 cm/sec), and it was estimated that the power required to treat 1000 gallons

would be about 60 kilowatts per hour (15 kilowatts per hour for each cubic meter treated.

74. Based on available data this system could theoretically be used to clarify disposal area supernatants, but the large quantities of flow that must usually be handled in most disposal areas would require extremely large filter surface areas. Although the removal efficiency of such a system would be expected to be excellent, the costs involved would be extremely high, thus rendering the system economically unfeasible.

Discussion

75. A wide variety of conventional solid-liquid separation technology has been reviewed in the foregoing paragraphs and various well known and readily available techniques and systems were described briefly; their performance capabilities were assessed; and, whenever possible, cost estimates (albeit very rough in many cases) were provided. In this section the merits and shortcomings of each of the systems and techniques in solid-liquid separation technology is discussed relative to their applicability in disposal area operations.

76. Sedimentation is a solids-liquid separation technique that is and should be widely used for the clarification of disposal area supernatants. The effectiveness of this technique depends on the size of the disposal area, the amount of flow through the area, the size of the suspended particles, and the degree of sediment agglomeration. For adequately large disposal areas, sedimentation with or without pretreatment may be the only process necessary to obtain effluents of the desired quality. Chemical pretreatment can be used to increase particle size and particle settling velocity, thereby improving clarification by sedimentation. Based on the data available thus far, lime appears to be an effective and relatively economical flocculant when applied to dredged material slurries as they are pumped into a disposal area; chemical costs may be about $0.80/ton of dry solids treated. Effluents of disposal areas can be treated with organic polymers and then allowed

to settle in order to achieve adequate clarification; polymer costs at this point of treatment will probably run about $0.60/ton of solids removed.

77. Filtration systems can be classified in either of two groups: one includes systems for dewatering dredged material slurries (solids content more than 1 percent by weight), and a second includes systems for clarifying disposal area supernatants. Alternatively, filter systems can be described as mechanized or nonmechanized. Mechanized systems require the use of pumps, piping, valves, and/or other control equipment and involve frequent cleaning or washing of the filter media; whereas, nonmechanized systems have little or no dependence on auxiliary equipment and require very limited maintenance. With respect to filtration mechanisms, surface filters use physical straining processes that remove solids by virtue of physical restrictions on a filter medium that has no appreciable thickness in the direction of flow, and depth filters retain solids throughout the total depth of the filter medium.

78. Vacuum filters appear to be feasible for dewatering dredged material slurries with up to 10 or 20 percent suspended solids by weight. However, they may not provide a highly clarified effluent without chemical preconditioning (effluent suspended solids on the order of 0.5 g/ℓ), and, for cases where strict effluent standards are enforced, a subsequent filter system may be required.

79. Centrifugation is a separation technique that very seldom involves the use of a filter medium. Excellent separation can be achieved for suspended particles with a specific gravity around 2.7 and diameters greater than 10μ; this implies that adequate pretreatment is required for effective solid-liquid separation of dredged material slurries, and even then, results may not be satisfactory. While centrifugation is often the most cost-effective design for large scale wastewater sludge disposal facilities, the capital costs are quite high. It is therefore suggested that at this juncture, centrifugation not be considered as a viable alternative for dewatering dredged material slurries.

80. Filter presses are generally used for retrieval of solids and not as a common dewatering process. Conventional designs require intermittent operation to allow for solids retrieval, cleaning the presses, and frequent application of a precoat. Few continuously operating systems are commercially available, and their performance is not yet well known or well documented. Therefore, pressure frame filters are also eliminated from further consideration, since they appear to offer no advantages over vacuum filters.

81. Belt systems, operating by either vacuum, pressure, or squeezing action, offer a reasonable alternative to rotary vacuum filtration; but additional pilot testing is desirable before accurate recommendations can be made on associated cost and effectiveness in their application to dewatering dredged material slurries. Speculations indicate that perhaps up to 50 percent cost reductions could be realized.

82. Wedge wire screens provide low suspended solids removal and are effective only for coarse particle sizes. Microscreens are normally used to polish effluents with low concentrations (100 mg/ℓ or less) of well-flocculated solids; however, no further treatment is usually required on disposal area effluents with 100 mg/ℓ or less suspended solids. In contrast, the Sonic Strainer is a very promising separation system because it can handle influents with suspended solids ranging from as low as 10 mg/ℓ to as high as 20 g/ℓ and can achieve removal efficiencies up to 99 percent. Available units can handle flows up to 0.12 m^3/sec (3 mgd) at low solids concentrations, but several units would be needed to handle influents with 20 g/ℓ suspended solids. Such units would have to be pilot tested before firm guidelines or recommendations could be made.

83. Precoat filtration can be economically used for waters with low turbidity (not more than 20 JTU), but it does not have good removal efficiencies for submicron particles. Therefore, precoat filters are not feasible for use in disposal area operations.

84. Electrofiltration is a clarification technique that is used primarily in laboratory investigations, and the economic feasibility

in full-scale field installations has not yet been documented. Although this method can provide excellent suspended solids removal efficiency, the slow flow rates associated with it and the resulting extremely large filter surface areas preclude its use at the present time for the clarification of disposal area effluents.

85. Conventional mechanized granular media filters can provide high retention efficiency (99 percent or more), but they are designed primarily to function economically only at low concentrations of suspended solids (up to 200 mg/ℓ). However, in most dredged material disposal operations, supernatants of such quality either need no further treatment or can be effectively clarified by simple nonmechanized systems. Although the use of conventional granular filter systems is not recommended, there are available a number of special designs that overcome some of the limitations of conventional designs. For example, available pressure filters can handle loads of suspended solids up to 1 or 2 g/ℓ with throughput rates of up to 1 cm/sec. Upflow filters and moving bed filters are available in various designs and have been documented to handle suspended solids loads of more than 1 g/ℓ. Specially designed granular filters appear to offer feasible solutions to the problem of clarifying disposal area supernatants with loads of suspended solids less than 1 g/ℓ. However, the performance of such systems is poorly documented in the literature, and it is considered necessary, as with conventional designs, to conduct pilot tests.

Slow sand filters or intermittent sand filters are good candidates for the treatment of water with reasonably high loads of suspended organic matter. Since disposal area effluents generally do not contain appreciable organic matter, this design is of limited general value. Because such slow rates are encountered, the required surface area would be extremely large and further increased by the need to provide for continuous drainage of the disposal area. Therefore, slow sand filters probably have little, if any, place in dredged material disposal area operations.

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